Land Information System

Submitted to CAN-00-OES-01: Grand Challenge Applications in the Earth, Space, Life, and Microgravity Sciences

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1. Science/Technology/Management

1.0.1 Abstract

Knowledge of land surface water, energy, and carbon conditions are of critical importance to real-world applications such as agricultural production, water resource management, and flood, weather and climate prediction. This has motivated the development of a pilot Land Data Assimilation Systems (LDAS), which integrates remotely-sensed and model-derived land surface data in a 4-Dimensional Data Assimilation (4DDA) framework. However, to fully address the land surface research and application problems, this system must be implemented globally at very high resolution (1km), and these predictions must be made transparently available to end users. This proposed Land Information System (LIS) will have the following components: (1) A high-resolution (1km) Global Land Data Assimilation System, involving several independent community land surface models, land surface data assimilation technologies, and integrated database operations for observation and prediction data management; and (2) a web-based user interface that accesses data mining, numerical modeling, and visualization tools. The LIS will be portable as demonstrated by applications on the ESS Teraflops Testbed as well as a custom-designed Cluster. LIS will help define land surface modeling and assimilation standards and will assist in the definition and demonstration of the Earth System Modeling Framework (ESMF).

1.0.2 Proposal Summary

Accurate initialization of land surface moisture, carbon, and energy stores in fully-coupled climate system models is critical for meteorological and hydrological prediction from days to seasons because of their regulation of surface water, carbon, and energy fluxes between the surface and atmosphere over a variety of time scales. Information about land surface conditions is also of critical importance to real-world applications such as agricultural production, water resource management, flood prediction, water supply, etc. This has motivated the development of Land Data Assimilation Systems (LDAS), which are ensembles of loosely-coupled land surface models that are forced and constrained by remotely-sensed and model-derived data in a 4-Dimensional Data Assimilation (4DDA) framework. An LDAS system has been successfully demonstrated for North America at 1/8 degree resolution in both real-time and long-term (50 years) retrospective simulations.

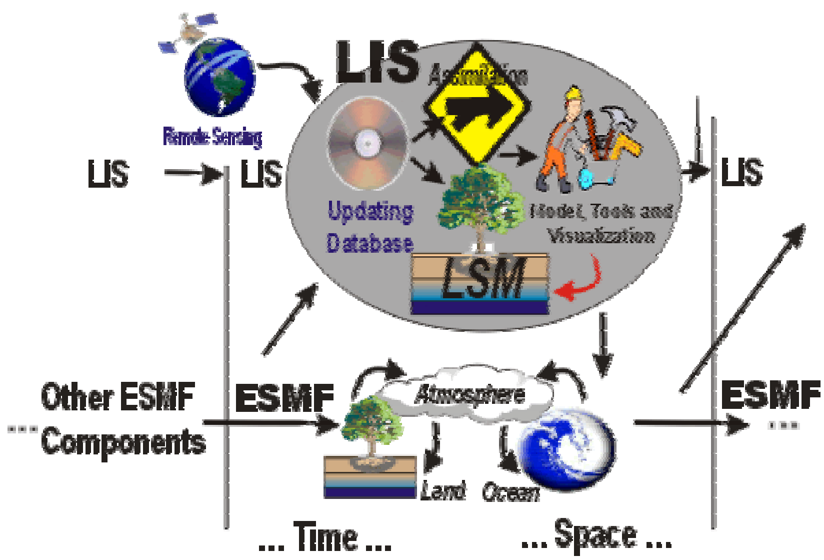


Figure 1: Interaction of the *Land Data Assimilation Scheme* (LDAS) with an operational *Numerical Weather Prediction* (NWP) system. The atmospheric *General Circulation Model* (GCM) is coupled with the *Land Surface Model* (LSM), and both use a *4-Dimensional Data Assimilation* (4DDA) process to integrate past forecasts with observations to improve performance.

However, to truly address the land surface initialization and climate prediction problem, as well as other critical water and carbon cycle applications, LDAS must be implemented globally at very high resolution (1km), and these predictions must be made transparently available to end users for use in various applications using a user-friendly, freely available, system independent, portable interface. The eventual computational requirements of this Land Information System (LIS) are estimated to be 1000 times larger than the current North American 1/8 degree LDAS (http://ldas.gsfc.nasa.gov), which itself is significantly limited by software and hardware engineering. However, we believe that this 1000 times increase is possible using massively parallel systems due to the relatively weak horizontal physical coupling of global land surface processes, which enables large-scale parallel processing software design.

The proposed Land Information System (LIS) will be a hardware transparent integrated software and database system, with the following components: (1) A high-resolution (1km) Global Land Data Assimilation System, involving several independent community land surface models (to avoid individual model bias and allow for inter-model ensemble studies), land surface data assimilation technologies, and integrated database operations for observation and prediction data management. This system will foster land model input-output standards that will enable common land model frameworks and encourage community standardization. (2) A web-based user interface, which at its basic level enables both data mining and visualization of land surface data from various in-situ, remote sensed, and modeled sources. However, LIS will go much further, allowing a user to actually use numerical models to explore various model/observation prediction scenarios for their given application in a cascading complexity user interface that will be usable by a wide range of clients. Several prototype user interfaces based on the Grid Analysis and Display System (GrADS) will be explored and enhanced in this project. The LIS will be portable as demonstrated by applications on the ESS Testbed as well as a custom-designed Linux Cluster. LIS will help define land surface modeling and assimilation standards and will assist in the definition and demonstration of the Earth System Modeling Framework (ESMF). In summary, LIS will enable important new research, applications, and outreach, but will require significant investment in frameworks for coupling as well as interoperability, parallel processing, storage, data distribution, and visualization in order to meet its goals.

1.1 Science Component

1.1.1 Program Relevance

"NASA is deeply committed to spreading the unique knowledge that flows from its aeronautics and space research...." (from http://www.nasa.gov). Earth science researchers and practitioners are increasingly inundated with land-surface observations and model output in disparate formats and locations. Land-surface observations have a great potential to benefit society, but often are overlooked due to a lack of expertise or facility. A vast array of very high-resolution global land surface observations are becoming available from the next generation of NASA earth science instruments (EOS Terra and Aqua), that we are not able to calibrate, interpret, or analyze at their native resolutions and in near-real time due to limits and bottlenecks in software, network, and hardware engineering. The significant real-world benefit of these observations and the model predictions and understanding that flow from them are within our ability if we task the correct resources.

There is a pressing need to understand the complex interactions between the various physical domains that comprise the water cycle. To observe these processes in sufficient detail to obtain that level of understanding is impractical at best. This difficult measurement problem is caused by such phenomena as the remarkable heterogeneity of moistening and drying of the soil layer at very small spatial scales. A more practical approach is to construct numerical models that incorporate the essential physics that govern these processes at very high resolutions, where we believe we understand their behavior, and then test the sensitivity of the process to a range of conditions. This approach can lead to a better understanding of the inherent nonlinear behavior of the process. From this understanding, we can develop algorithms to improve the representation of these processes in coarser resolution models of the entire hydrologic cycle. To develop the simulation capability described above requires a consistent computational framework that permits both the testing of various algorithms that represent specific processes, and their coupling across the physical domains that describe the water cycle. This requirement demands that modularity and code standardization protocols be a primary component of the computational framework to promote intercomparison of particular algorithms. The framework must also allow for parallel computing in a loosely coupled manner, so that individual process models, that together can describe the water balance of a region, can be run simultaneously, yet independently, passing information as needed with other process models.

Therefore, we propose the development of a near-real-time, high-resolution (eventually 1km global) Land Information System (LIS) that will provide knowledge of land surface water, energy, and carbon conditions transparently for use in critical real-world applications and Earth System Modeling (Figure 1). Our overarching hypothesis is that land surface simulation, observation, and analysis methods are sufficiently advanced to accurately determine global land-surface energy, carbon, and moisture stores at the high resolution required by most applications. This project is clearly a *grand challenge* in that it addresses a range of critical real-world land-surface science and application problems, and that it requires a significant increase (estimated to be about 1000 times the current state-of-the-art) in software, hardware, and communication performance. Global high-resolution land surface processes have not been addressed by previous HPCC investigations, and it is clear that there is great potential such a focus to contribute to other Earth science grand challenge in the development of a land-ocean-atmosphere Earth System Modeling Framework (ESMF).

Due to the very high resolution and near real time need of land surface information, the use of scalable parallel computing technology is critically important and relevant. Land surface processes have rather weak horizontal coupling on short time and large space scales, which enables highly efficient scaling across massively parallel computational resources. The only two obstructions to significant land surface model efficiency on parallel computers are the relatively high data intensity of land models, and the need to explicitly treat significant horizontal model and observation error covariance in high-resolution land surface data assimilation systems. Addressing these issues will be a significant focus of this project.

NASA's Earth Science Enterprise has recently released a new research strategy (http://www.earth.nasa.gov/visions/research_strat/overview_5.1.html), that outlines its research mission for the next 10 years, which is to develop a scientific understanding of the Earth system and its response to natural or human-induced changes and improve prediction capabilities for climate, weather, global air quality and natural hazards. The ESE mission will be accomplished by assessing the current state, the primary forcings, the responses, consequences, and predictability of the Earth system. LIS addresses the land surface component of all these questions, and goes farther by linking them with community research and educational frameworks that ***spread the unique knowledge that flows*** from ESE observations. More specifically, LIS will address linkages between the global water and energy cycle, climate variability and prediction, and the biophysical processes which are three of the major ESE scientific focus topics. The proposed research is further relevant to the NASA-ESE science goals of developing methods to use satellite remote-sensing to improve the assessment and prediction of land surface hazards such as floods, droughts, etc., and assessing the impact of land cover and use on the Earth system. This project is also relevant to a variety of international research programs, through its provision of critical land surface data sets of interest to CLIVAR, GOALS, and GEWEX.

The availability and quality of water is essential to life on earth: Accurate assessment of the spatial and temporal variation of the global land surface water cycle is essential for addressing a wide variety of highly socially relevant science, education, application, and management issues, and is central to the mission of NASA's Earth Science Enterprise. Land surface data assimilation techniques are being developed to assess and predict critical hydrologic information. With this proposal, NASA has the opportunity to make unique and significant contributions to water cycle issues by integrating its the unique view from space and innovative interpretation tools such as data assimilation, which is only truly possible using high performance computing.

Furthermore, the proposed research is distinct, yet complementary to the land surface data assimilation activities currently being undertaken by NASA's Data Assimilation Office (DAO), and NASA's Seasonal-to-Interannual Prediction Project (NSIPP) at Goddard Space Flight Center (GSFC). The very high-resolution realistic land surface conditions produced by LIS using state-of-the-art, newly emerging land-surface observation, simulation, and analysis technology in an operational context, will significantly benefit both NSIPP and DAO. The principal investigator has been actively involved in both NSIPP and DAO, so experience gained by these groups in high performance computing and software engineering will be directly transferable to this project.

1.1.2 Science Rationale

Here, we briefly review the current science behind the proposed Land Information System (LIS), and forward the components we plan to use, namely (1) land surface remote sensing, (2) land surface modeling, and (3) land surface data assimilation. We then present the Land Data Assimilation System (LDAS) as the science prototype for LIS.

Land Surface Remote Sensing: A huge volume of land surface observations are being or may be operationally sensed from space, including surface temperatures, vegetation conditions, snow, albedo, longwave and solar radiation, precipitation, surface moisture, freeze/thaw state, runoff, total water storage, elevation, among others. An emphasis of the proposed research is to compile and assimilate those highly dynamic remotely-sensed observations of the land surface that previous research suggests will provide memory to land-atmosphere interaction. Remote observations of interest include temperature, soil moisture (surface moisture content, surface saturation, total water storage), other surface water bodies (lakes, wetlands, large rivers) and snow (areal extent, snow water equivalent). Generally, surface temperature remote sensing can be considered an operational technology, with many spaceborne sensors making regular observations (i.e. Landsat TM, AVHRR, MODIS, and ASTER) [Lillesand and Kiefer, 1994]. The land surface emits thermal infrared radiation at an intensity directly related to its emissivity and temperature. Some errors due to atmospheric absorption and improperly specified surface emissivity are possible, and the presence of clouds can obscure the signal. The evolution of land surface temperature is linked to all other land surface processes through physical relationships which we exploit in a data assimilation framework to correct all of the predicted land surface states. Remote-sensing of soil moisture content is a developing technology, although the theory and methods are well established [Eley, 1992]. Long-wave passive microwave remote-sensing is ideal for soil moisture remote-sensing, but there are technical challenges in correcting for the effects of vegetation and roughness. The EOS-Advanced Microwave Sounding Unit (AMSR) instrument will provide C-band microwave observations that may be useful for soil moisture determination when it is launched in 2001. The TRMM-TMI, which is very similar to AMSR, is much better suited to soil moisture measurement (because of its 10 Mhz channels) than SSM/I, and is also currently available. All of these sensors have adequate spatial resolution for land surface applications, but have a very limited quantitative measurement capacity, especially over dense vegetation. However, Sipple *et al*., [1994] demonstrated that it is possible to determine saturated areas through dense vegetation using SMMR, which can greatly aid land surface predictions. Because of the large error in remotely-sensed microwave observations of soil moisture, there is a real need to maximize its information by using algorithms (such as the proposed methods) that can account for its error and that extend its information in time and space. An important and emerging technology with respect to this project is the potential to monitor variations in total water storage (ground water, soil water, surface waters (lakes, wetlands, rivers), water stored in vegetation, snow and ice) using satellite observations of the time variable gravity field. The Gravity Recovery and Climate Experiment (GRACE), an Earth System Science Pathfinder mission, will provide highly accurate estimates of changes in terrestrial water storage in large watersheds when it is launched in 2001. Wahr *et al*. [1998] note that GRACE will provide estimates of variations in water storage to within 5 mm on a monthly basis. Rodell and Famiglietti [1998] have demonstrated the potential utility of these data for hydrologic applications, including their application in large (>150,000 km^2) watersheds; and they further discuss the potential power of GRACE for constraining modeled water storage in land surface models when combined with surface soil moisture and altimetery observations. Birkett [1995, 1998] demonstrated the potential of satellite radar altimeters to monitor height variations over inland waters, including climatically-sensitive lakes and large rivers and wetlands. Such altimeters are currently operational on the ERS-2 and TOPEX/POSEIDON satellites, and are planned for the ENVISAT and JASON-1 satellites. Key snow variables of interest in this work include areal coverage and snow water equivalent. While the estimation of snow water equivalent by satellite is currently in research mode, snow areal extent can be routinely monitored by many operational platforms, including AVHRR, GOES and SSM/I. Recent algorithm developments even permit the determination of the fraction of snow cover within Landsat-TM pixels [Rosenthal and Dozier, 1996]. Cline *et al*. [1998], describe an approach to retrieve SWE from the joint use of remote sensing and energy balance modeling. The feasibility of implementing this approach on a global scale will be explored in the context of this research.

Modeling of the Land Surface: Recent advances in understanding soil-water dynamics, plant physiology, micrometeorology, and the hydrology that control biosphere-atmosphere interactions have spurred the development of Land Surface Models (LSMs), whose aim is to represent simply yet realistically the transfer of mass, energy, and momentum between a vegetated surface and the atmosphere [Dickinson *et al*., 1993; Sellers *et al*., 1986]. LSM predictions are regular in time and space, but these predictions are influenced by model structure, errors in input variables and model parameters, and inadequate treatment of sub-grid scale spatial variability. Consequently, LSM predictions are significantly improved through the use of observations. Three recent LSMs warrant further discussion with respect to this project. These are the Variable Infiltration Capacity (VIC) LSM (Wood et al.), the **N**ational Centers for Environmental Prediction (NCEP), **O**regon State University (OSU), United States **A**ir Force (USAF), and Office of **H**ydrology (OH), LSM, called **NOAH**, and the recently emerging Community Land Model (CLM).

The NOAA-NOAH LSM simulates soil moisture (both liquid and frozen), soil temperature, skin temperature, snowpack water equivalent, snowpack density, canopy water content, and the traditional energy flux and water flux terms of the surface energy balance and surface water balance. This model has been used in a) the NCEP-OH submission to the PILPS-2d tests for the Valdai, Russia site, b) the emerging, realtime, U.S.-domain, Land Data Assimilation System (LDAS), c) the coupled NCEP mesoscale Eta model [Chen *et al*, 1997] and the Eta model's companion 4-D Data Assimilation System (EDAS), as well as in d) the coupled NCEP global Medium-Range Forecast model (MRF) and its companion 4-D Global Data Assimilation System (GDAS).

The Community Land Model (CLM) is being developed by a *grass-roots* collaboration of scientists who have an interest in making a general land model available for public use. By *grass roots*, we mean that the project is not being controlled by any single organization or scientist, but rather, the scientific steering is judged by the community. However, the project began at a sub-group meeting at the 1998 NCAR CSM meeting, and there is a plan to implement the CLM into the NCAR CSM by early 2001. The CLM development philosophy is that only proven and well-tested physical parameterizations and numerical schemes shall be used. The current version of the CLM includes superior components from each of three contributing models: LSM (G. Bonan, NCAR), BATS (R. Dickinson) and IAP (Y.-J. Dai). The CLM code management will be similar to *open source*, in that, use of the model implies that any scientific gain will be included in future versions of the model. Also, the land model has been run for a suite of test cases including many of the PILPS (Project for the Intercomparison of Land Parameterization Schemes) case studies. These include FIFE (Kansas, USA), Cabauw (Netherlands), Valdai (Russia), HAPEX (France), and the Amazon (ARME and ABRACOS). These cases have not been rigorously compared with observations, but will be thoroughly evaluated in the framework of the Project for the Intercomparison of Land-surface Parameterization Schemes (PILPS).

The first version of the Variable Infiltration Capacity (VIC) model is described in detail by Liang et al. (1994) and Liang et al. (1996a). As compared to other SVATS, VIC's distinguishing hydrologic features are its representation of subgrid variability in soil storage capacity as a spatial probability distribution, to which surface runoff is related (Zhao et al., 1980), and its parameterization of base flow, which occurs from a lower soil moisture zone as a nonlinear recession (Dumenil and Todini, 1992). As discussed by Lohmann et al. (1998a, b) the representation of soil hydrology (soil water storage, surface runoff generation and sub-surface drainage) has a critical influence on the predicted long-term water and energy balances.

Justification for using an uncoupled LSM: There are strong justifications for studying an LSM uncoupled from atmospheric and ocean models. While, coupling the LSM to an atmospheric model allows for the study of the interaction and feedbacks between the atmosphere and land surface. However, coupled modeling also imposes strong land surface forcing biases predicted by the atmospheric model on the LSM. These biases in precipitation and radiation can overwhelm the behavior of LSM physics. In fact, several NWP centers must 'correctively nudge' their LSM soil moisture toward climatological values to eliminate its drift. By using an uncoupled LSM, we can better specify land surface forcing using observations and address virtually all of the relevant scientific questions. A goal of the LIS project is to participate as a land surface modeling "customer" for the developing Earth System Modeling Framework (ESMF), preserving the recognized benefits of offline modeling. We propose to accomplish this through reciprocal participation with the ESMF team on each projects' technical advisory board, and ultimately a demonstration and evaluation of an ESMF prototype in the LIS.

Carbon Cycle Analysis and Prediction: A new generation of land-surface parameterizations has emerged in recent years in which exchanges of water and heat at the vegetated land surface are linked to exchanges of CO_2 (Sellers *et al*, 1997). This linkage is based on the fact that physiological control of evapotranspiration by plants is an evolved optimization mechanism that seeks to maximize carbon fixed by photosynthesis (by drawing CO_2 into leaves through stomatal pores) and yet reduce water loss from the plant (by closing stomata). The representation of this linkage in land-surface parameterizations has been shown to improve the simulated diurnal cycle of temperature and humidity. It also allows key parameters controlling surface exchanges to be related to the spectral reflectance characteristics of vegetation (Sellers *et al*, 1996a,b). This carbon-water linkage also opens the door for the models to predict the flux of CO_2 in a self-consistent way with simulated surface energy exchanges and turbulent and convective transport in the atmosphere (Denning *et al*,1996a,b). Simultaneous prediction of CO_2 in addition to energy and water fluxes allows more rigorous evaluation of model output against observations, and leads to better constraint of model parameters.

Under separate funding (NASA EOS-IDS, Inez Fung, PI), SiB2 is being extended to include calculation of carbon and nitrogen cycling and storage in below-ground pools, and to include an optional prediction of seasonal vegetation phenology. This functionality will be included in the LIS, allowing estimation of high-resolution spatial and temporal patterns of CO_2 fluxes and pools as they respond to physical climate forcing. This product would not include CO_2 fluxes due to other processes (such as fossil fuel combustion, forestry activity, fires, etc). Nevertheless, detailed flux maps could be prescribed as boundary forcing to atmospheric transport codes and the resulting concentration fields compared to observations. Extending the prediction of the land surface fluxes to include biogeochemical as well as physical exchanges will add potentially assimilable new information to the LIS.

Land Surface Data Assimilation: Charney *et al*. [1969] first suggested combining current and past data in an explicit dynamical model, using the model's prognostic equations to provide time continuity and dynamic coupling amongst the fields. This concept has evolved into a family of techniques known as *four-dimensional data assimilation* (4DDA). "Assimilation is the process of finding the model representation which is most consistent with the observations" [Lorenc, 1995]. In essence, data assimilation merges a range of diverse data fields with a model prediction to provide that model with the best estimate of the current state of the natural environment so that it can then make more accurate predictions (see Figure 2). The application of data assimilation in hydrology has been limited to a few one-dimensional, largely theoretical studies [i.e. Entekhabi *et al*., 1994; Milly, 1986] primarily due to the lack of sufficient spatially-distributed hydrologic observations [McLaughlin, 1995]. However, the feasibility of synthesizing distributed fields of soil moisture by the novel application of 4DDA applied in a hydrological model was demonstrated by Houser *et al*. [1998]. Six Push Broom Microwave Radiometer (PBMR) images gathered over the USDA-ARS Walnut Gulch Experimental Watershed in southeast Arizona were assimilated into the TOPLATS hydrological model using several alternative assimilation procedures. Modification of traditional assimilation methods was required to use these high density PBMR observations. The images were found to contain horizontal correlations with length scales of several tens of kilometers, thus allowing information to be advected beyond the area of the image. Information on surface soil moisture was also assimilated into the subsurface using knowledge of the surface-subsurface correlation. Newtonian nudging assimilation procedures were found to be preferable to other techniques because they nearly preserve the observed patterns within the sampled region, but also yield plausible patterns in unmeasured regions, and allow information to be advected in time.

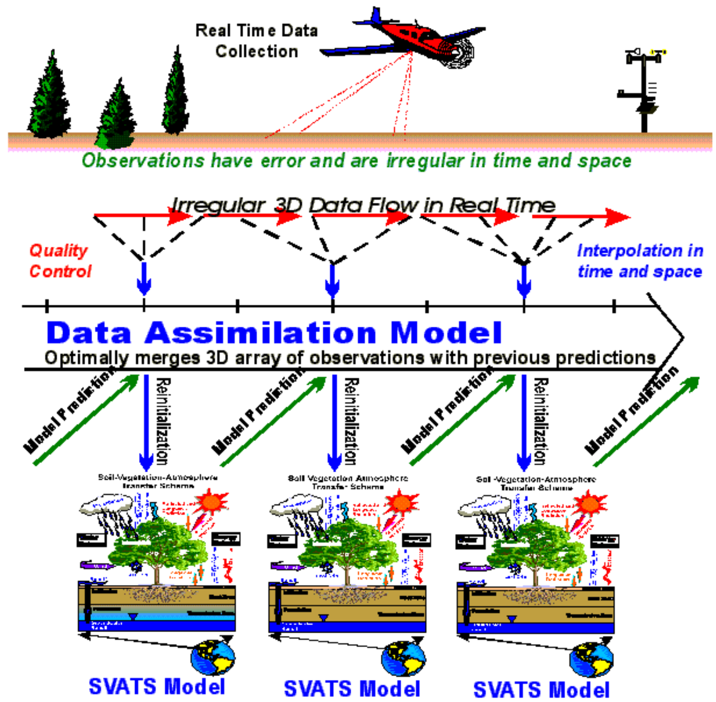
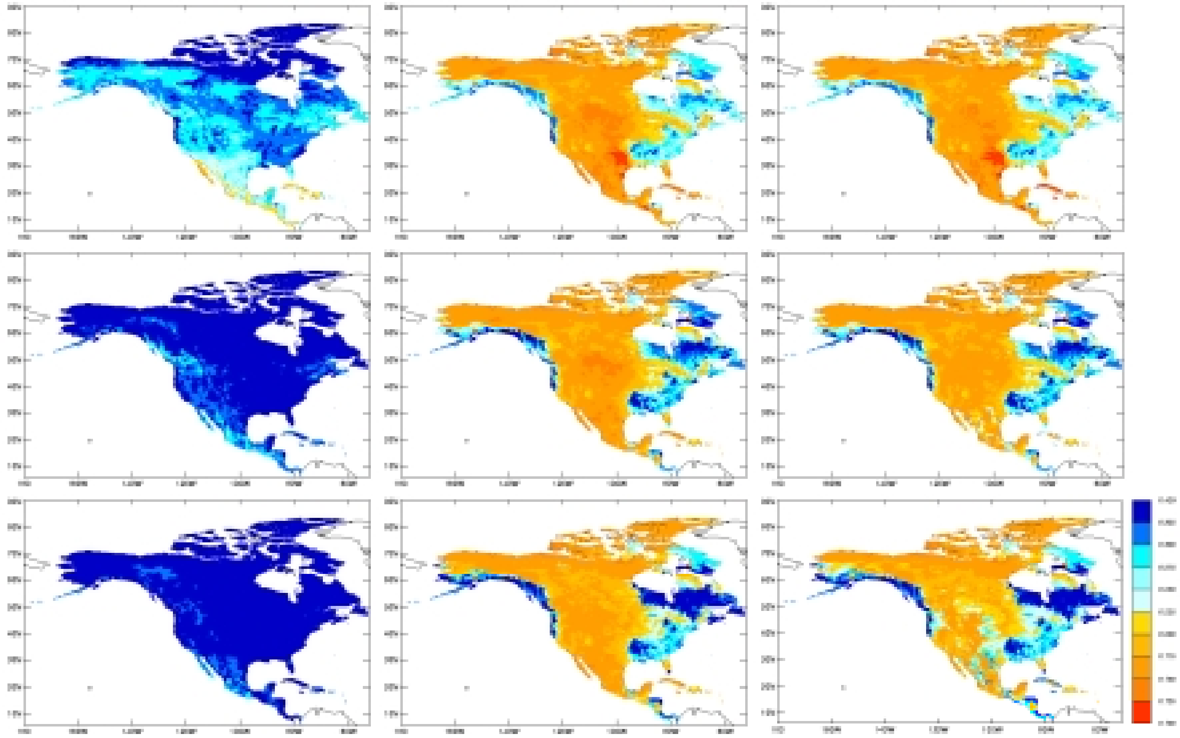


Figure 2: The land surface data assimilation process.

A great deal of research is currently underway at GSFC, NCEP, and several other institutions to develop land surface data assimilation methods for soil moisture, surface temperature, and snow. There are also ongoing efforts at GSFC to assimilate radiance information directly, and to use alternate assimilation methodologies. We will therefore work in close collaboration with these efforts to implement the best land-surface assimilation strategies. In this research, we plan to use a Kalman filtering based land assimilation strategy that expands upon the, largely theoretical assimilation algorithms developed Entekhabi *et al.* [1994] and Milly, [1986], and the four-dimensional data assimilation strategies developed by Houser *et al.* [1998] and Walker *et al.* [1999]. The Kalman filter attempts to obtain an optimal estimate of a land surface state by combining observations of that state with an LSM forecast of that state. The Kalman filter has been extensively utilized in data assimilation research [Ghil *et al*., 1981; Cohn, 1982]. The Kalman filter assimilation scheme is a linearized statistical approach that provides a statistically optimal update of the system states, based on the relative magnitudes of the covariances of both the model system state estimate and the observations. The principal advantage of this approach is that the Kalman filter provides a framework within which the entire system is modified, with covariances representing the reliability of the observations and model prediction.

A set of numerical experiments have been undertaken for North America to illustrate the effectiveness of the assimilation scheme in providing a more accurate estimate of the soil moisture storage throughout the entire soil profile. Using the LSM of Koster *et al*. [2000], the initial conditions from spin-up, and the model input data described above, the temporal and spatial variation of soil moisture across North America was forecast for 1987. The forecasts of near-surface soil moisture were output once every 3 days to represent the near-surface soil moisture measurements from remote sensors. In addition to soil moisture, the land surface model provided estimates of evapotranspiration and runoff for each of the catchments. This simulation provided the "true" soil moisture and water balance data for comparison with degraded simulations. Moreover, it allowed evaluation of the effectiveness of assimilating near-surface soil moisture data for improving the LSM forecast of soil moisture and water budget components, when initialized with poor soil moisture initial conditions. In the degraded



a) b) c)

Figure 3: Comparison of soil moisture (v/v) on 30 January 1987 in near-surface (top row), root zone (middle row) and entire profile (bottom row) from: a) simulation with degraded initial conditions for soil moisture; b) simulation with spin-up initial conditions ("truth"); and c) degraded simulation with assimilation of near-surface soil moisture from the "truth" once every 3 days.

simulation, the initial conditions for the soil moisture prognostic variables from the spin-up were set to arbitrarily wet values uniformly across the entire North America. The LSM was then forced with the same atmospheric data as in the previous simulation. The wet initial condition causes over-estimation of evapotranspiration and runoff. The final simulation was to assimilate the near-surface "observations" from the "truth" simulation into the degraded simulation once every 3 days. The effect of assimilation on the soil moisture forecasts can be seen in Figure 3. These results show that after only 1 month of assimilation, the "true" soil moisture has been retrieved for the majority of North America.

Most data assimilation methods used in large spatially distributed problems involve solving very large systems of equations which require extensive computational resources. In operational environments, the data assimilation process is a computationally intensive task: it is repeated with the periodicity of the incoming observation data. This leads to a real-time requirement that a single assimilation cannot take longer than it takes the natural world to evolve. In fact, for a real-time forecast, everything added together including data assimilation, forecast simulation, other data gathering and manipulations/analysis, etc., must be done in real-time.

Land Data Assimilation Systemss (LDAS): The characterization of the spatial and temporal variability of water and energy cycles is critical for the improvement of our understanding of land surface-atmosphere interaction and the impact of land surface processes on climate extremes. Because accurate knowledge of these processes and of their variability is important for climate predictions, most NWP centers have incorporated land surface schemes into their

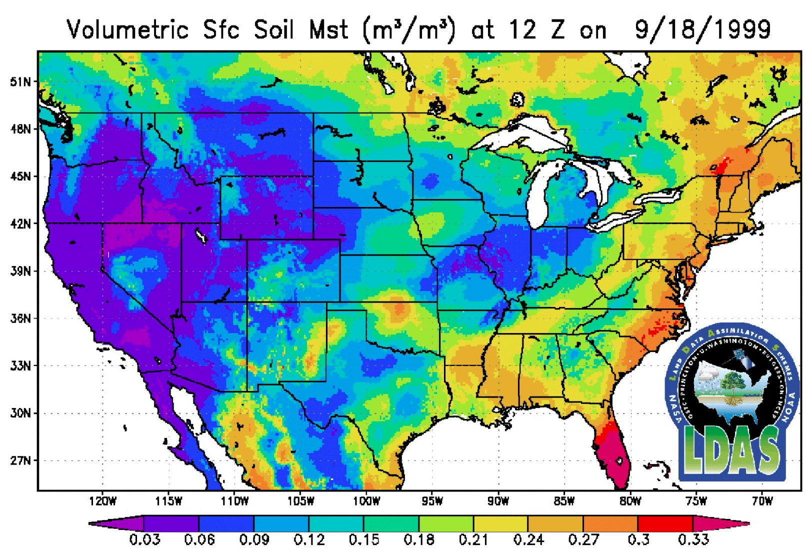


Figure 4: A near-real time LDAS soil moisture field.

models. However, errors in the NWP forcing accumulate in the surface and energy stores, leading to incorrect surface water and energy partitioning and adversely affecting related processes. This has motivated the NWP centers to impose ad hoc corrections to the land surface states to prevent this drift. *Land Data Assimilation Systems* (LDAS), which are uncoupled land surface schemes that are forced primarily by observations, and are therefore not affected by NWP forcing biases are currently under development [Brutsaert *et al*., 1998]. This research is being implemented in near real time using existing LSMs by NCEP, NASA, Princeton University, and the University of Washington at a 1/8th° (about 10 kilometer) resolution across the United States to evaluate these critical science questions. The LDAS are forced with real time output from numerical prediction models, satellite data, and radar precipitation measurements. Model parameters are derived from the high-resolution EROS vegetation coverages.

A real-time LDAS system is currently in place (please see http://ldas.gsfc.nasa.gov), that uses near-real time NCEP Eta model analysis fields, along with observed precipitation and radiation fields to force several different land surface models in an uncoupled mode (see Figure 4). Forcing, parameter, resolution, and prediction specifications for this North-American LDAS were carefully chosen by the LDAS working group.

1.1.3 Science Community

The international land surface modeling community, which includes the hydrology, biogeochemistry, biogeophysics, land-atmosphere interaction, soil physics, solid earth, natural hazards, etc. sub groups is strongly fractured into highly specialized, small, independent research communities. This is especially evident when projects such as the Project for the Intercomparison of Land surface Parameterization Schemes (PILPS) (Henderson-Sellers et al., 1993) identifies literally hundreds of land surface models whose differences must be understood and quantified. Fortunately, through recent community efforts such as PILPS, Land Data Assimilation Systems (LDAS), Community Land Model (CLM), and the Global Energy and Water Cycle Experiment (GEWEX), land surface modeling communities are being built. However, we have a long way to go to integrate the land surface water, energy, carbon, nitrogen, and vegetation research communities, and even farther to go to include operational prediction, management, and applications, where 1960's pre-satellite methods are commonplace.

Our strategy to include the community in LIS and deliver its new capabilities is to (1) continue expanding and integrating the LDAS, CLM, and GEWEX land-surface community efforts, (2) to optimize the functionality and portability of LIS using established methods and frameworks, (3) to develop a LIS working group to include wider community in its development and application, (4) integrate the land modeling and assimilation components of the NASA NSIPP and DAO projects, and (5) develop explicit public outreach and educational applications. Here we further describe the scientific community efforts in which several of the investigators of this project participate, and through which LIS will find great application and use.

LDAS Community: The *Land Data Assimilation Systems* (LDAS) community has developed from the integration of several independent research teams that are developing various aspects of uncoupled land surface schemes that are forced primarily by observations, in near real time by NCEP, GSFC, the NWS Office of Hydrology, Princeton University, and the University of Washington at a 1/8th° (about 10 kilometer) resolution across the United States. This community has been extremely successful at defining common parameter datasets, input and output model data standards, and has established a land surface forcing data set of unprecedented quality. Since the announcement of these standards, many land modeling groups (Rutgers University, University of Maryland, University of Arizona, COLA, etc.) have joined the LDAS group, and many others are using LDAS data in diverse research projects.

CLM Working Group: The Community Land Model (CLM) is being developed by a *grass-roots* collaboration of scientists who have an interest in making a general land model available for public use. The CLM working group comprises about 20 scientists from government, academia, and the private sector, which is an unparalleled in the land community. CLM is being coupled to the NCAR Community Climate System Model, the Data Assimilation Office (DAO) next generation data assimilation system, and is in use at COLA.

GEWEX Community: The GEWEX Modeling and Prediction Panel (GMPP) is working in association with the Working Group on Numerical Experimentation (WGNE) to meet its commitment to assist in the production of improved cloud and land-surface parameterizations for use in General Circulation Models (GCMs). There was endorsement of plans to move forward with a GEWEX Global Land/Atmosphere System Study (GLASS), which was formulated by the community in a series of workshops. GLASS has four main activity elements, which correspond to work on off-line and coupled functions at both the point to regional scales and the global scale. Development of a standardized interface that will facilitate the inter-comparison activities within GLASS is also underway.

LIS Working Group: In collaboration with NASA-ESE, and the land-surface modeling community, we propose the organization of a LIS land working group with the goals of encouraging complementary ideas and collaboration from a larger research group and developing potential LIS applications. This group will be comprised of researchers, and potential end users that could help to maximize the practical development and use of our proposed research. Annual meetings, and regular email or conference call discussions will help to refine both the research proposed here, and LIS land research in general.

1.2 Technology Component

Earth science researchers and practitioners are increasingly inundated with land-surface observations and model output in disparate formats and locations. Land-surface observations have a great potential to benefit society, but often are overlooked due to a lack of facilities or expertise. Therefore, as a second major component of LIS (the first being LDAS), is the development of interactive land modeling, analysis, and modeling tools which will enable scientists, students, practitioners, and managers to interactively access, analyze, compare, understand, and validate land-surface information. LIS will consist of a set of ***interactive web_based data analysis tools*** based on the latest World Wide Web, hardware, and ***land-surface modeling technologies***, and will be linked via a public interface to real-time land surface observations and model analysis. The LIS will not only allow users to access and visualize NASA data, but will also allow them to interactively use land surface models to explore countless "what-if" situations. This capacity to include interactive modeling in a web interface is pioneering, and will set a new standard for access to NASA data. LIS will be implemented with the intention of porting it to remote workstations for independent or linked operation.

1.2.1 Frameworks and Interoperability

To achieve our science and application goals, we must set a primary goal to improve software quality, reduce duplication of effort, enhance interoperability, and promote community cooperation by developing a common software infrastructure that can be shared by many scientists and practitioners. This interoperability framework must provide distributed/parallel computing functions, data access and distribution, security, and multicast services. LIS software will be implemented with the goals of achieving high performance in near-real time, tools to monitor and manage performance, object-oriented design and interfacing, allowance for concurrent development of applications and software, the ability to scale to different time/space resolutions, computer platforms, and land regions, allow for the easy incorporation of new data types and model components, be fully open-source for community use, and be fully integrated with Java and WWW interfaces.

Given that an ESMF prototype will not be available until late in the project, we plan to use the already existing community LDAS, CLM, and ALMA frameworks in this project, which have been previously described: ***Land Data Assimilation Systems (LDAS)* –** LDAS is data and model framework developed by an international research and weather prediction operational community that is in need of land surface initialization for use in weather and climate forecasts. ***Community Land Model (CLM)* –** CLM is a U.S. community (centered around NCAR) land model development framework for developing generalized yet advanced land model physics and code. ***Assistance for Land-surface Modeling Activities (ALMA)*** – ALMA is a land-atmosphere coupling framework standard that is being developed by the broad land-atmosphere research community. As part of our Year 3 milestones, we will demonstrate and evaluate a prototype of the ESMF within the LIS.

We will actively interact with educators, scientists, technologists, and the public to maximize LIS use and applicability. Because of the flexibility, portability, and power we design LIS with, it will likely be appealing to multiple groups; each group will have to be approached in a different way to encourage use of LIS. Therefore, the proposed LIS advisory working group will encourage complementary ideas and collaboration from a larger research group and developing potential LIS applications. Beyond this, we also plan to bring LIS to the public, as follows: **Educators:** Teachers, K-12 will be reached in multiple ways. We will maintain close ties with current NASA educational programs, such as the GLOBE project as well as NASA's Classroom of the Future. We also plan to present LIS at educational conferences, giving demonstrations of how it can help them brooch multiple Earth science topics with their students. **Scientists:** We plan to enlist the scientific community's involvement in LIS through conference presentations and written publications. We plan to use the GrADS example. GrADS was originally developed by Brain Doty, at the University of Maryland, so at first it was only used by people there. However, it was such a powerful and useful tool, for manipulating meteorological data, that it began to spread. Now, scientists from all over the globe use GrADS. Their demands and comments have sparked Mr. Doty to continually add new features to it. Similar feedback from the scientific community will help us to make LIS more useful for scientific research. **Technologists:** Computer hardware and software technology is continuously changing. Data storage and processing technologies are improving at astounding rates. Our eye will always be on the cutting edge and we will focus on bring appropriate new hardware and software to LIS. In this way, LIS will continually provide additional capabilities at faster speeds. **Public:** Public availability and interactions with public agencies will help us enhance LIS with public outreach functions.

Our geographic location close to the nation's capitol gives us the opportunity to interact with policy makers, government officials, and their aides.

LIS Security Issues: LIS presents a potential security risk due to its highly interactive nature. Therefore care will be taken to assure the integrity of NASA systems. A queuing system will be developed that will prevent the main LIS server from being overloaded. The widespread success of the LIS concept may fairly quickly overwhelm the requested resources, in which case NASA information technologists will be consulted to help meet the demand. LIS will be designed to be a fully scalable and portable system, so it will easily expand to use additional computer resources as demand requires. Further, any user wishing to submit a job run, i.e. a more processor intensive activity, will have to receive permission to do such. Finally, LIS will be designed to prohibit the distribution of sensitive data or information, and data that is not available for free distribution.

Extensive LIS User Help and Support**:** The incorporation of sophisticated graphics and data handling used in LIS may seduce the user into a false sense of model accuracy, when these features neither increase nor diminish the fundamental correctness of the model results. Graphical features will be extremely valuable for visualizing land-surface data, but the user must be careful that this visualization enhances what is known rather than hiding assumptions and uncertainty. The "user friendliness" of LIS introduces further concern. These systems will be used by individuals who have little scientific expertise. Land-surface models have become increasing complex, with numerous assumptions and parameters that are not always comprehensible to the experienced modeler, let alone to novice users (Grayson, *et al.*, 1993). So it is essential that these systems have ample help and support, so as not to lead users astray. Therefore, LIS will be implemented with a detailed overview and usage page, as well as multiple help windows for each subsection of the menu. A list of frequently asked questions and a users Email group will be maintained. Finally, it must be stressed that LIS is a experimental learning and research tool; it is not an operational forecast system, so we can not guarantee or be liable for its forecasts and predictions.

1.2.2 Applications

The proposed Land Information and Prediction System (LIS) has several major software components, most of which already exist in some form. These are admittedly in various forms of formal software engineering maturity, and in some cases significant recoding may be required. LIS will draw heavily on the current, highly modular Fortran 90 Land Data Assimilation Systems (LDAS) driver code, the Fortran 90 Community Land Model (CLM) model physics code, the C++ Variable Infiltration Capacity (VIC) model physics code, the Fortran 77 NOAH model physics code, the Grid Analysis and Display System (GrADS) visualization software, and the Java/Perl LDAS-Real-time Image Generator (RIG) interactive web visualization code (see http://ldas.gsfc.nasa.gov).

The ***Grid Analysis and Display System*** (GrADS) (Doty, 1995) will be the primary data visualization tool used in LIS. GrADS is an interactive desktop tool that was specifically designed for the analysis and display of earth science data and is currently in use worldwide. GrADS is implemented on all commonly available platforms and is freely distributed. It implements a 4-Dimensional data model with dimensions of latitude, longitude, altitude, and time. Each data set is located within this 4-Dimensional space by use of a data description file. Both gridded and station data may be displayed. GrADS files may be binary, GRIB, HDF, or NetCDF. Since each data set is located within the 4-D data space, intercomparison of disparate data sets is greatly facilitated. Operations may be performed between data on different grids, or between gridded and observational data. Disparate data may be graphically overlaid, with correct spatial and time registration.

The internet has the potential to serve as an ideal distribution network for scientific data. In order for this potential to be realized, the problems of large data set size and data set analysis must be addressed. The GrADS (Grid Analysis and Display System)-DODS (Distributed Ocean Data System) product created by Brian Doty seeks to do just that.

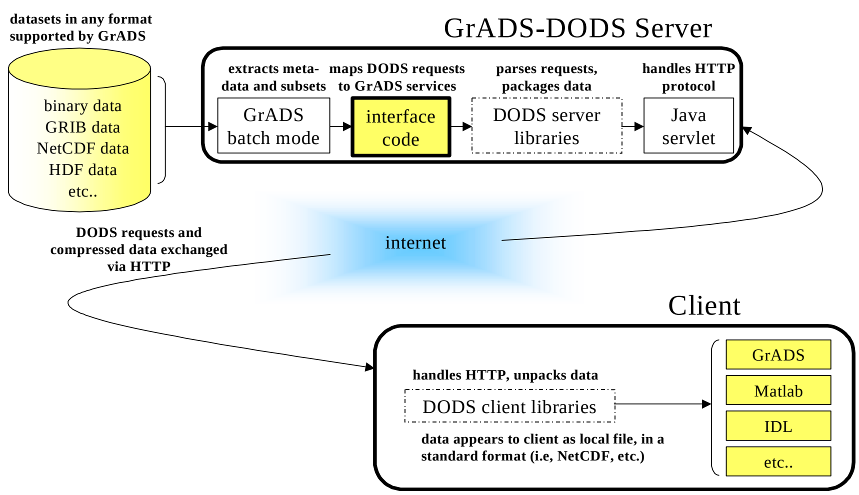


Figure 3: GrADS-DODS system schematic.

GrADS-DODS is a joining of a data analysis program (GrADS) with a data access system (DODS). A fully featured research tool which can access such data types as netCDF, binary and GRIB, GrADS offers an ideal way to visualize gridded data sets. Many similar data analysis tools require a complete copy of the dataset to be locally available in order to function. Even if one only wishes to analyze a particular time or spatial subset of the data, the entire dataset must first be transferred to a local machine. This can become problematic, as the transfer of remotely stored large data sets to local machines may be impractical or impossible. By contrast, the GrADS-DODS product requires that only the data subset of interest be transferred to a local machine. Specifically, users of the system can specify in GrADS the subset of data that they wish to study. This data request is passed using URL text to a DODS server which subsets the data and sends this reduced data set back to the GrADS program running on the local computer. This subset may be a temporal or spatial subset, and may be the product of mathematical operations performed on one or more remote data sets. This makes the transfer of full data sets unnecessary and shifts the computational burden off of the local machine and onto the remote server; actions which greatly improve efficiency. The truly remarkable part: **you don't have to rewrite the code** to enable an application to work as a DODS client. DODS follows a client-server model, and has a comprehensive User's Guide. Most importantly, GrADS and DODS are free and public.

1.2.3 Parallel Computing

Due to the very high resolution and near real time need of land surface information, the use of scalable parallel computing technology is critically important and relevant. Land surface processes have rather week horizontal coupling on short time and large space scales, which enables highly efficient scaling across massively parallel computational resources. The only two obstructions to significant land surface model efficiency on parallel computers are the relatively high data intensity of land models, and the need to explicitly treat significant horizontal model and observation error covariance in high resolution land surface data assimilation systems. Addressing these issues will be a significant focus of this project.

A goal of the LIS project is to participate as the coupled land component of an Earth System Modeling Framework (ESMF), preserving the recognized benefits of using an uncoupled model. We propose to accomplish this through a loosely coupled ESMF framework, were each ESMF component provides the best available estimate of boundary fluxes to other ESMF, based on model ensembles combined with observations. Due to their large database and physics, ESMF components will likely be independent executables that share information using a common earth system interface standard (there are currently very active efforts to define these standards).

1.2.4 Milestone Metrics

We propose to develop the Land Information System, which improves and enables interoperability with the CLM, LDAS, and GrADS framework codes. The project milestones have been identified in section 5 along with quantified metrics stating the degree of improvement. These metrics for each software improvement milestone are in units of quality valued by the relevant science community or flight projects, which for the land surface community are typically based on spatial domain and resolution, timing of solution, number of data sets used for initialization, validation, or assimilation, and the community involvement in the LIS framework.

1.2.5 Data Handling

At the heart of LIS will be the numerous data sets that may be accessed for analysis or modeling purposes. As there are an extremely large number of land-surface data sets now available, inclusion of data into the LIS archive will be based on extensive consultation and cooperation with land-surface modeling experts both within, and outside of, NASA. Although much of the data will be retrospective, a large quantity will be current and so will need to be constantly updated. A robust system for performing this task on a reduced scale is already operating at the LDAS web site mentioned above. Here, C shell scripts and FORTRAN programs combine to gather data from new model runs or observation cycles, and to store such data in locations appropriate for interactive use. This system is completely automated, including safety fallbacks, and can easily be expanded for use with LIS. Whenever possible, links to large land surface data on other NASA systems (such as at the DAACs) will be made, rather than storing the data locally. An automatically updating index of available data and time/space availability will be maintained to optimize database operations.

The LIS database system is envisioned to be completely automated, including safety fallbacks, platform independent, and extremely scalable. As the retrieval scripts will be open-ended and generic, inclusion of new data sets into the LIS archive will necessitate only minor changes in code. Similarly, the storage requirements of new data sets are taken care of by the open-ended nature of the LIS storage system. This system will be based on a combination of RAID disk arrays and tape archival systems. This hardware has been used successfully in the LDAS project and has proved to be easily scalable to meet any storage needs. In addition, links to large land surface data bases on other NASA systems (such as the DAACs) will be made whenever possible, which will serve to minimize local storage needs. Database operations will be further streamlined through use of an automatically updating index of available data and time/space availability. And finally, LIS users will have the option to post their own data for use in their own analyses or for use by others.

Beyond the base LIS database, automatically produced model analysis, as well as user requested analyses will need to be managed by LIS database operations. This will require a significant data storage capacity. Based on our experience with LDAS, we estimate that about 10 terabyte of disk storage will be required in the pilot stage of LIS, with increasing requirements as the system matures.

LIS is envisioned as a valuable research tool for those in specific as well as interdisciplinary sciences. As such, data holdings need to be diverse and will span a broad range of Earth sciences. In order to assemble an optimal set of data, inclusion of data into the LIS archive will include the following categories:

1) ***Satellite remote-sensing*** land surface data and products such as temperature, NDVI vegetation greenness, snow cover, moisture, etc. from LANDSAT, AVHRR, GOES, SSM/I, TRMM, CERES, ASTER, MISR, MODIS, various airborne sensors.
2) ***Land-surface properties*** such as vegetation (USGS-EROS, UMD), soils (STATSGO, PSU), elevation (DEMs), and MODIS products.
3) ***Runoff*** from stream gauges and relevant watershed information.
4) ***Near-surface meteorological*** data from model reanalysis, operational analysis, and forecasts, and surface observations. Of particular relevance is SNOTEL and NEXRAD precipitation observations.
5) ***Land model data*** from several well known land surface models included in LIS. (Possible models include CLM, MOSAIC, NOAA-NOAH, SiB, BATS, ViC, etc.).
6) ***User-defined datasets*** gives the user a real opportunity to customize LIS for their own application.

The databases described above are of little value without an efficient user interface. Therefore, the second project task will be to implement and refine the proposed LIS web_tools shown in Figures 1 and 3. This interface will depend heavily upon the use of HTML, JavaScript, Perl, C shell and Fortran 90 languages to provide the degree of interactivity needed for LIS. It will be intuitive, with content_based and traditional_style retrieval forms enabling the user to quickly and efficiently select relevant data sets. Users will be able to analyze existing data sets, map data from one projection to another, execute user_defined model simulations, and perhaps even include their own land model or analysis algorithm in LIS. They will also be able to create and explore subsets of original data sets, precluding the need to download the large, cumbersome full data set. Geographical sub-setting will be available by region, watershed, state, or user-defined box. Specialized analysis tools will also be available to derive watershed hydrologic information. Scripts written in JavaScript, Perl and C Shell will gather and process user input, and send relevant information to image processors such as GrADS, or to ftp utilities that will gather or deliver data as necessary. Like the data collection system mentioned above, this system already exists on a reduced scale at the LDAS web site (http://ldas.gsfc.nasa.gov).

This practical combination of programming tools leads to a flexible and intuitive environment where users can perform anything from simple analyses to complex, customized model runs. We will perform this task by first revising and optimizing the desired full web interfaces, depending on data availability, and then by making each of the options operational one-at-a-time. Before the system is made public, it will be thoroughly tested and evaluated to eliminate errors and optimize usability. In summary, LIS will be developed to perform the following primary functions: (1) Understand a query made by the LIS user; (2) Locate and retrieve the most responsive datasets or model analyses; (3) If requested, perform land model integrations with user conditions; (4) Retrieve, interpolate, analyze, and subset the data; (5) Resolve spatial relationships between diverse data (point, raster, resolution, swath, etc) (6) reformat the data and make it available to the user; (7) graphically visualize the data using GrADS or other appropriate software. We expect to offer several common land-surface process models on LIS, including CLM, VIC, NOAH, etc, with coupled runoff routing tools to facilitate comparison with streamflow observations.

We realize that not every user will have the same background, or level of expertise in using LIS. Therefore the LIS user interface will be designed to allow for cascading complexity depending on the level of user's need to control the system. This interface would allow for very straightforward interaction with students or the general public, and a more comprehensive set of "pull-uot" options for use by expert land modelers and researchers. We also plan to include tutorial interface pages that a user could use to learn the LIS interface. Finally, a LIS 'highlights' page will be available, which shows a number of example LIS applications performed by LIS users.

1.2.6 Previous Work

The LIS team has significant parallel computing experience in the land surface and land-atmosphere scientific domains. Various members of the team are formal science team members of, and are actively involved in large-scale scientific parallel computing in the NSIPP, DAO, NCAR, NCEP, COLA, and the North Carolina Supercomputing Center projects. These projects and centers have all been highly successful in porting code across platforms, and implementing it efficiently across large numbers of processors. The investigators have experience running on various SGI, Cray, IBM, and Linux supercomputing systems.

Since the reviewers are likely aware of ongoing COLA, DAO, NSIPP, and NCEP high performance computing, we will provide a example of previous work performed at the North Carolina Supercomputing Center. Peters-Lidard et al., (1999) showed that by taking advantage of similarities in hydrological behavior, a new version of the TOPMODEL-based Land Atmosphrere Transfer Scheme (TOPLATS; Famiglietti and Wood, 1994; Peters-Lidard et al., 1997; 1998), can be applied with computational performance approaching that of a much simpler LSP while retaining the complex soil-vegetation-topographical details of the original TOPLATS. Because the new model makes use of sparse-matrix operations for aggregation and disaggregation, it has been named Sparse-TOPLATS. Further, Peters-Lidard et al., (1999) designed a model-coupling interface approach which consists of: (1) a drop-in MM5V2 (Grell et al., 1995) module MCPL() (Coats, 1998) that provides selective direct access to MM5V2 outputs variable-by-variable; (2) a module which reads Sparse-TOPLATS fluxes and aggregates them for use by MM5V2; (3) drop-in Sparse-TOPLATS modules that perform mirror functions (output to MM5V2 and disaggregation of MM5V2 data for use by Sparse-TOPLATS); (4) a Parallel Virtual Machine (PVM) (Geist et al., 1994; PVM, 1998)-based interface (Coats et al., 1999) that allows the two models to coordinate with each other and exchange data, while retaining their own fundamental spatio-temporal physical and computational characteristics. In addition, they describe how these

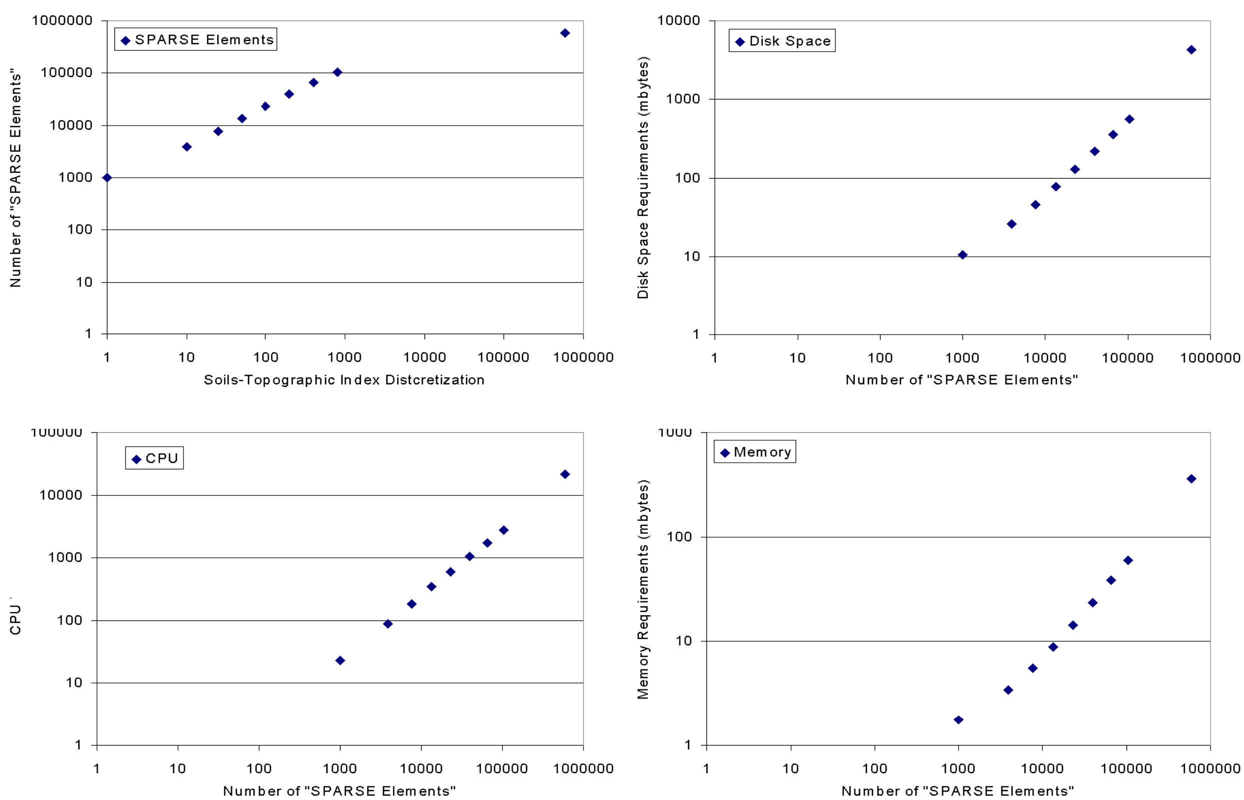


Figure 5: Storage, memory, and CPU requirements of the TOPLATS-MM5 coupling.

building blocks are extended to data-assimilation mode, whereby GOES-derived solar radiation and NEXRAD Stage IV precipitation may be used to drive the coupled model system at the land-atmosphere interface. Finally, they discuss how this approach will enable modelers to better reconcile modeled water-budget calculations with observations.

1.3 Management Component

The proposed work will be conducted in close collaboration between NASA's Goddard Space Flight Center (GSFC), a wide variety of university, government and private science organizations, and will draw much support from interdisciplinary community collaboration. The LIS team will consist of an interdisciplinary team of 14 well-qualified scientists, software engineers, programmers, and students with complementary expertise. Dr. Paul Houser (0.1 MY) will be responsible for overall project direction and coordination, and will provide scientific input for land surface simulation and data assimilation strategies. Dr. Christa Peters-Lidard (0.5 MY will act as Co-PI and Project Manager. Dr. Peters-Lidard will coordinate the software engineering, parallel code implementation, and construction of the cluster.

A collaborative working relationship has been established with other researchers working on *Land Data Assimilation Schemes* (LDAS). Dr. D. Lettenmaier (Univ. of Washington), and Dr. J. Schaake (NWS Office of Hydrology) will collaborate on the development of a runoff routing scheme to update and validate the LIS, and we will collaborate on the general development, implementation, and validation of the LIS. We will also collaborate with Dr. Randy Koster at GSFC on upgrades to LSM modeled processes.

1.3.1 Project Team

We have assembled a complete and balanced team, containing necessary backgrounds and skills in the team including the physical and computational/computer scientists and the software engineers. The background and responsibilities of each investigator are listed here.

P. R. Houser (PI;NASA/GSFC): ***Dr. Houser***'s area of expertise is local to global land surface-atmospheric observation and numerical simulation, development and application of hydrologic data assimilation methods, and multi-scale soil moisture investigations. ***Dr. Houser***'s primary responsibility will be the management and coordination of the LIS team. ***Dr. Houser*** will also provide scientific input into the realistic representation of the surface meteorology and hydrology in the coupled land-atmosphere model. Further, ***Dr. Houser*** is a pioneer in the development of the LDAS and CLM frameworks, and has extensive experience in software engineering, hydrologic web tool development, graphic visualization, land modeling, data assimilation, and remote sensing. Finally, ***Dr. Houser*** is a member of both the NASA/GSFC DAO and NSIPP teams, and thus will provide a vital intellectual and software/hardware engineering link to these groups.

C. Peters-Lidard (Co-PI;NASA/GSFC): ***Dr. Peters-Lidard*** focuses on measurement and modeling of terrestrial water and energy balances and fluxes due to land-atmosphere interactions over a range of temporal and spatial scales. This research encompasses the areas of micrometeorology, boundary layer meteorology, field experiments, hillslope hydrology, hydrometeorology, numerical modeling, spatial data analysis, and remote sensing. ***Dr. Peters-Lidard*** has extensive experience with massive parallel coupled land-surface atmospheric models, and will have a primary responsibility in this area. Further, she will facilitate many aspects of education and public outreach, clustered high performance computing, atmospheric coupling, earth system model connections, and advanced software engineering. ***Dr. Peters-Lidard*** will have significant leadership, management, and intellectual responsibilities, acting on the Co-PI level.

P. Dirmeyer (Co-I;COLA): ***Dr. Dirmeyer*** conducts research into the role of the land surface in the climate system. This includes development and application of land-surface models, studies of the impact of the land on the predictability of climate, and the impacts of land use change on regional and global climate. ***Dr. Dirmeyer*** is chair of the GEWEX global soil wetness project (GSWP), and as such has developed extensive community infrastructure frameworks and tools, such as the ALMA land surface model standards. ***Dr. Dirmeyer*** will be responsible for LIS software standards, the Community Land Model (CLM) framework, will provide input to atmosphere coupling, earth system models, and software engineering. ***Dr. Dirmeyer*** will also serve as a collaboration mechanism with GSWP, ISLSCP, and COLA.

B. Doty (Co-I;COLA): Brian Doty has over 20 years of in-depth experience in a wide range of computing technologies. He developed the Grid Analysis and Display System (GrADS) package that is used worldwide for climate data analysis and visualization, and he is currently developing distributed web-based analysis and search tools for geophysical data, including both model output and remote sensing products. He will be primarily responsible for the application of the GrADS-DODS Server (GDS) software to the LIS, in particular its support of remote users who wish to access and analyze high resolution land surface model output and remote sensing data sets. He will also initiate the work toward utilizing parallel data analysis techniques from within GrADS to permit rapid access and computation on the very large data sets envisioned in this project.

K. Mitchell (Co-I;NCEP): ***Dr. Mitchell*** is primarily responsible for land modeling and its coupling to the Eta model at the National Center for Environmental Prediction. He is the major developer of the NOAH land model, its NWP connections, and is a leader in the LDAS community framework. As part of an operational center, ***Dr. Mitchell*** has extensive experience with efficient land model coupled code implementation on very large compute platforms (1179 Gflop IBM SP Power3 – currently the 6th largest in the world). In this project, ***Dr. Mitchell*** will be responsible for LIS atmosphere connections, earth system model connections, operational software engineering and data support, and LDAS collaborations.

E. Wood (Co-I;Princeton): ***Professor Wood***'s specialty is hydroclimatology, with research focuses in land-atmospheric interactions, terrestrial remote sensing, hydrologic impacts from climate change, and environmental data analysis. His modeling focuses on the terrestrial water and energy balances and fluxes due to land-atmospheric interactions over a range of temporal and spatial scales, and his remote sensing research is concerned with estimating land surface model forcings and the hydrologic and energetic states of the terrestrial system. ***Professor Wood*** will be responsible for the inclusion of the VIC model in LIS, various aspects of LIS remote sensing, and general hydrologic modeling and analysis. ***Professor Wood*** will also serve as the senior science advisor for LIS.

S. Denning (Co-I; CSU): ***Professor Denning*** investigates the interface between terrestrial ecosystems and the atmosphere, with particular emphasis on using atmospheric observations to understand the global carbon cycle. His research involves the development and application of simulation models of these interactions across a wide variety of spatial and temporal scales to apply the strongest possible observational constraints on the carbon budget of the atmosphere. He emphasizes the "fusion" of modeling and data analysis to understand natural processes. ***Professor Denning*** will be responsible for the land surface biogeochemistry and carbon cycle remote sensing and modeling aspects of LIS.

Post-Docs (2): Two post docs at NASA-GSFC will be responsible for LIS science coordination and implementation, and database development and the software engineering associated with parallel implementation. TBD **Software Engineering Support (1)**: One software engineer at COLA will be responsible for the GrADS-DODS modifications required by LIS. One **research assistant** will assist Professor Wood in fulfilling his responsibilities to this project at each of their respective institutions.

1.3.2 Project Management

The proposed work will be managed by the Hydrological Sciences Branch at NASA's Goddard Space Flight Center (GSFC). The LIS team will consist of 14 well-qualified scientists, and software engineers, with complementary expertise. A collaborative working relationship has been established with other relevant land-surface researchers through the LDAS, CLM, and ALMA partnership.

1.4 Conclusion

The proposed Land Information System will provide scientists, students, practitioners, and the general public with user adaptive access to a wide array of land surface data, and the ability to seamlessly analyze, visualize, and model land surface processes. Because LIS will be developed in collaboration with a broad community, its analysis, capabilities, and efficiency will far exceed what could be obtained by an individual, and will comply with standard practices.

***Return on Investment*:** LIS is a relatively straightforward and inexpensive way to greatly enhance the accessibility and usability of NASA observations. The potential return on investment of LIS is large. LIS can help NASA scientists and engineers to understand the value of existing sensors, and help them to design increasingly superior instruments. LIS will greatly facilitate use of NASA data and products by scientists, students, and the public across the globe. For the first time, LIS will put research-quality land-surface modeling tools in the hands of educators who can use them to fuel the creativity of their students without bogging them down in the complexities of data format issues. Finally, it is quite possible that through LIS, NASA observations could improve the understanding of natural hazards (such as floods, droughts, and landslides), land use change and agriculture, which could have a large positive economic impact.

Land Information System

Submitted to CAN-00-OES-01: Grand Challenge Applications in the Earth, Space, Life, and Microgravity Sciences

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2. Software Engineering Plan

Experience shows us that there must be clarity and planning if there is to be the proper completion of the task. We have clearly outlined the LIS task above, and we feel that while ambitious, it will provide a significant contribution to NASA's expertise within the time frame of this project. SEI (Software Engineering Institute) software engineering and management tools will be employed to assure high-quality LIS software development. This includes regular internal formal technical reviews to evaluate the developing LIS against the requirements outlined above, to formally introduce new LIS ideas and concepts, and to derive metrics of LIS success. Furthermore, we will adhere to ISO9001 requirements that are based on common sense project management and well known principles of quality science, as is required at NASA-GSFC.

The end-to-end LIS is a complex operation that must be implemented using modern software engineering methods [Pressman, 1993]. There are large numbers of people directly involved in LDAS and LIS research and operations. The need for software engineering has become apparent in a complex environment where issues such as formal software testing, configuration management (CM), version control and maintenance, multiple hardware

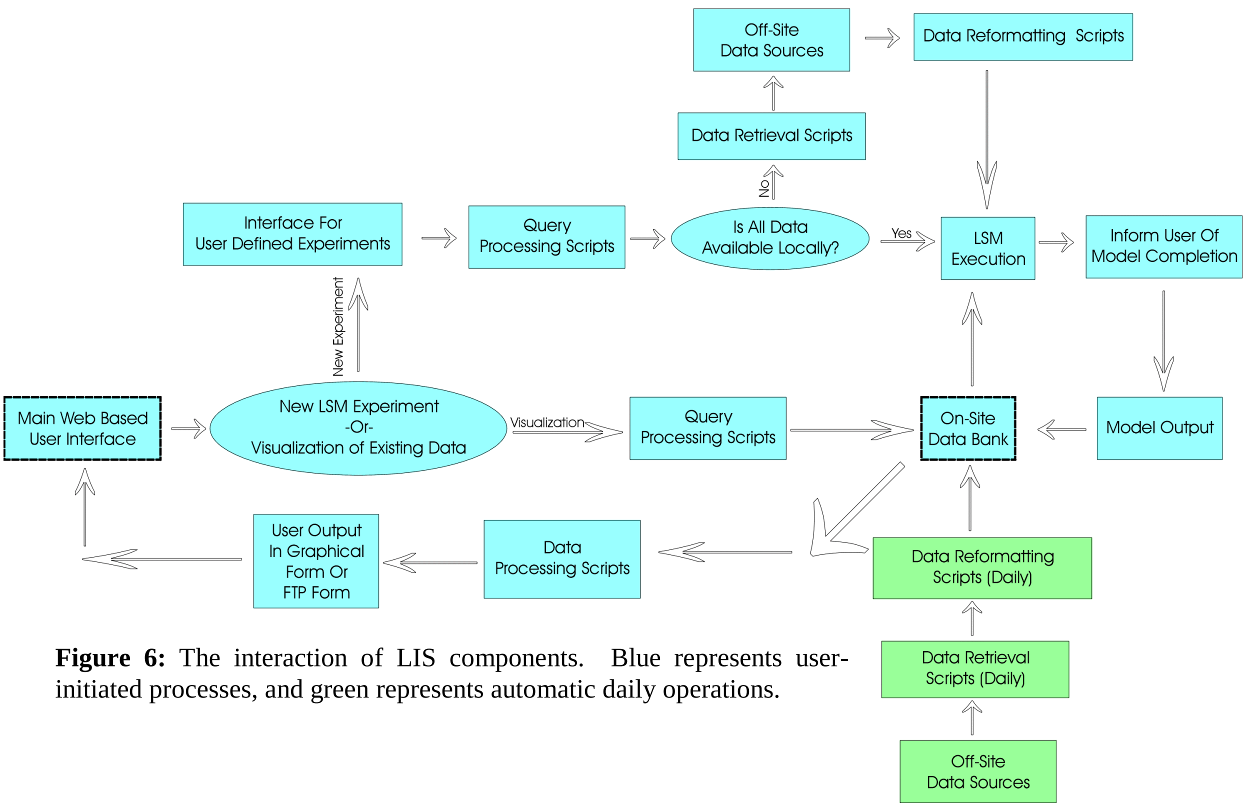

Figure 6: The interaction of LIS components. Blue represents user-initiated processes, and green represents automatic daily operations.

platforms, and the coordination of distributed personnel are important. The LDAS team enthusiastically embraced software engineering and CM after it became apparent that the organization had reached critical mass in terms of personnel and technology. For the development of LIS, we plan to use the formal software engeneering methods, tools, and procedures, including a process of information engineering, customer communication, analysis, design, code generation, documentation, change control, repository support, prototyping tools, testing, re-engineering, formal technical reviews, and complete assessment of metrics.

The proposed Land Information System consists of several well defined tasks: The construction of the LIS web tools, the establishment of a database and database operations to support it, and the interaction with potential LIS users. These tasks will be undertaken in a milestone framework as laid out by the CAN. The capabilities of database operations, the availability of various observations, and the feedback from the user community will help to define the capability and development of the LIS system. The individual LIS components will be virtually transparent to the user, whose only interaction with the system will be through a web-based interface. A brief description of the development and functionality of the components of LIS are given below, and a flow chart showing the interaction between various LIS components is shown in Figure 6.

Further, we will develop a middleware layer between a commercial operating system and the LIS applications to enable fault tolerance mechanisms from which the applications can make selections based on their reliability and efficiency requirements. The first version of the middleware layer will demonstrate reliability based on software implemented fault-tolerance (0.99 over 5 years), scalability (50 nodes), and portability for all REE applications. A later revision will add real-time capability as a feature.

GrADS-DODS Software Engineering Focus: The GrADS-DODS Server (GDS) software is ideal for the implementation of LIS, in particular its support of remote users who wish to access and analyze high resolution land surface model output and remote sensing data sets. We will work toward utilizing parallel data analysis techniques from within GrADS to permit more rapid access and computation on the very large data sets envisioned in this project.

The GrADS (the Grid Analysis and Display System) and DODS (the Distributed Ocean Data System) will be a central focus of the interoperability of the LIS.   GrADS, when linked with the DODS-enabled netCDF library, can access datasets and subsets of datasets over the network or internet from DODS servers. Metadata retrieved from the servers is used by GrADS to facilitate comparison of different data, either by overlaying displays of data from different sources or via analytical techniques.

In addition, the GrADS and DODS technologies have been combined on the server side. The GrADS-DODS server allows DODS-enabled clients to retrieve arbitrary subsets of all the data formats that GrADS can handle, including GRIB. In addition, the GrADS-DODS server extends the capabilities of DODS by providing analysis capability on the server side.   This greatly expands the utility of the client-server concept. For example, if one wants to average a large amount of data, all that data must be moved to the client in the case where the server only provides the ability to do simple subsetting. With the GrADS-DODS analysis server, the calculation can be performed at the server, with only the (fairly small) result being transmitted back to the client.

The GrADS-DODS server goes beyond the typical DODS server in a very powerful way – it supports general analysis capability on the server. In a research environment, it is difficult to predict what a scientist might want to do with the data. Even simple operations on the data (such as averaging) might require bringing the entire data set to the scientist’s desktop. This defeats some of the purpose of DODS. With the analysis capability of the GrADS-DODS server, it is much less likely that the scientist will feel compelled to transfer the entire data set to local disk.

DODS is a software package that helps users provide and access data over the net in a consistent fashion. DODS is a highly distributed system due to the two fundamental considerations that have gone into the design of DODS:

- data are often most appropriately distributed by the individual or group that has developed them; and
- the user will in general like to access data from the application software with which s/he is most familiar.

Although DODS was originally designed and developed by oceanographers and computer scientists for oceanographic data, there is nothing in the design of DODS that constrains its use to oceanography. Indeed, it has been adopted by the High Altitude Observatory community and is being considered by segments of the meteorological and space science communities.

The DODS tools for developing network-savvy versions of popular data access APIs and data analysis packages extend the scope of an application's search for data. A DODS-enabled application can:

- Get any data anywhere on the Internet that is served by a DODS server.
- Use data from any DODS server, pretty much regardless of its native format.
- Still perform all its original functions for accessing data locally.

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Land Information System

Submitted to CAN-00-OES-01: Grand Challenge Applications in the Earth, Space, Life, and Microgravity Sciences

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Data assimilation research that integrates hydrologic observations into land surface process models.
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Houser, P. R., 1999: Infiltration and Soil Moisture Processes. In Handbook of Weather, Climate, and Water, edited by T. Potter and B. Bradely.
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Research and Teaching Experience

Research Scientist. NASA/GSFC Hydrological Sciences Branch, July 2001-present. Conduct hydrometeorologic and hydroclimatologic research on measurement and modeling of land-atmosphere interactions.

Assistant Professor. School of Civil and Environmental Engineering, Georgia Institute of Technology, December 1996-present (on leave through August 2002). Taught undergraduate and graduate courses in Hydrology. Conduct independent research program on measurement and modeling of land-atmosphere interactions.

Research/Teaching Assistant. Water Resources Program, Department of Civil Engineering and Operations Research, Princeton University, Princeton, New Jersey. July 1991-November 1996.

Hydrologic Technician. United States Geological Survey, Water Resources Division, Reston/Richmond, Virginia. Digitized and constructed domains for hydrodynamic modeling using ARC/INFO. May-August 1990, May-August, December 1989.

Honors/Awards

NASA/ASEE Summer Faculty Fellow at GSFC, 1997
George Van Ness Lothrop Honorific Fellowship in Engineering, 1995-1996
National Science Foundation Graduate Fellow, 1992-1995
Phi Beta Kappa

Professional Service

National Research Council Committee on Hydrologic Science (1999-2001)
American Geophysical Union Technical Committee on Precipitation (1997-2001)
American Geophysical Union Technical Committee on Remote Sensing (1997-present)
American Meteorological Society Hydrology Committee (1999-2003)

Selected Publications (Reverse Chronological)

Peters-Lidard, C. D., F. Pan, and E. F. Wood, 2001. A re-examination of modeled and measured soil moisture spatial variability and its implications for land surface modeling. *Advances in Water Resources (Special Issue on Non-Linear Propagation of Multi-scale Dynamics Through Hydrologic Subsystems),* **24**/9-10, pp 1069-1083.

Peters-Lidard, C. D. and L. H. Davis, 2000: Regional Flux Estimation in a Convective Boundary Layer Using a Conservation Approach. *AMS Journal of Hydrometeorology*, **1**, 170-182.

Coats, C. J., Jr., A. Trayanov, J. N. McHenry, A. Xiu, A. Gibbs-Lario, and C. D. Peters-Lidard, 1999: An Extension of the EDSS/Models-3 I/O API for Coupling Concurrent Environmental Models, with Applications to Air Quality and Hydrology. *Preprints: 14th Conference on Hydrology, American Meteorological Society, Dallas, Texas*

Peters-Lidard, C. D., E. Blackburn, X. Liang and E. F. Wood, 1998: The Effect of Soil Thermal Conductivity Parameterization on Surface Energy Fluxes and Temperatures. *J. Atmos. Sci.,* **55** (7), 1209-1224.

Peters-Lidard, C. D., M. S. Zion and E. F. Wood, 1997: A Soil-Vegetation-Atmosphere Transfer Scheme for Modeling Spatially Variable Water and Energy Balance Processes, *J. Geophys. Res.*, **102** (D4), 4303-4324.

Paul Alan Dirmeyer

Work Address:
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Education:
Ph.D. in Meteorology, December 1992, University of Maryland at College Park. Dissertation title: GCM Studies of the Influence of Vegetation on the General Circulation: The Role of Albedo in Modulating Climate Change.
M.S. in Meteorology, December 1988, University of Maryland at College Park. Thesis title: Stationary Solutions in a One Layer Spectral Model.
B.S. in Meteorology (Magna Cum Laude), May 1986, Texas A&M University.

Employment:
1993-current: Research Scientist at the Center for Ocean Land Atmosphere Studies (a Center within the Institute of Global Environment and Society).

Positions:
Chair: GEWEX Global Soil Wetness Project (GSWP).
Member: International Satellite Land-Surface Climatology Project (ISLSCP) Science Panel.
Member: GEWEX Land Atmosphere System Study (GLASS).
Member: US-CLIVAR Pan American Panel.
Member: NCAR Climate System Model -- Land Model Working Group, CLM Development Group.
Special Member of the Graduate Faculty: University of Maryland at College Park.
Adjunct Member of the Graduate Faculty: George Mason University (Virginia).

Selected Publications:
Dirmeyer, P. A., F. J. Zeng, A. Ducharne, J. Morrill, and R. D. Koster, 2000: The sensitivity of surface fluxes to soil water content in three land surface schemes. J. Hydrometeor., 1, 121-134.
Dirmeyer, P. A., 2000: Using a global soil wetness data set to improve seasonal climate simulation. J. Climate, 13, 2900-2922.
Reale, O. and P. Dirmeyer, 2000: Modeling the effects of vegetation on Mediterranean climate during the Roman classical period. Part I: History and model sensitivity. Global and Planetary Change, 25, 163-184.
Dirmeyer, P. A., A. J. Dolman, and N. Sato, 1999: The Global Soil Wetness Project: A pilot project for global land surface modeling and validation. Bull. Amer. Meteor. Soc., 80, 851-878.
Dirmeyer, P. A., and F. J. Zeng, 1999: SSiB sensitivity to infiltration and treatment of convective precipitation. J. Meteor. Soc. Japan, 78, 291-303.
Dirmeyer, P. A. 1999: Assessing GCM sensitivity to soil wetness using GSWP data. J. Meteor. Soc. Japan, 78, 367-385.
Dirmeyer, P. A., and K. L. Brubaker, 1999: Contrasting evaporative moisture sources during the drought of 1988 and the flood of 1993. J. Geophys. Res., 104, 19383-19397.
Oki, T., T. Nishimura, and P. Dirmeyer, 1999: Assessment of annual runoff from land surface models using Total Runoff Integrating Pathways (TRIP). J. Meteor. Soc. Japan, 78, 235-255.
Dirmeyer, P. A., 1998: Land sea geometry and its effect on monsoon circulations. J. Geophys. Res., 103, 11,555-11,572.
Dirmeyer, P. A., and J. Shukla, 1996: The effect on regional and global climate of expansion of the world's deserts. Quart. J. Roy. Meteor. Soc., 122, 451-482.
Dirmeyer, P. A., 1995: Problems in initializing soil wetness. Bull. Amer. Meteor. Soc,76, 2234-2240.
Dirmeyer, P. A., 1994: Vegetation stress as a feedback mechanism in mid latitude drought. J. Climate, 7, 1463-1483.
Dirmeyer, P. A. and J. Shukla, 1994: Albedo as a modulator of climate response to tropical deforestation. J. Geophys. Res., 99, 20,863-20,877.
Dirmeyer, P. A. and J. Shukla, 1993: Observational and modeling studies of the influence of soil moisture anomalies on atmospheric circulation. Prediction of Interannual Climate Variations (ed. by J. Shukla), NATO Series I, Vol. 6, Springer-Verlag, 1-23.

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Experience (some concurrent):

1997-current	Director of Information Systems, Center for Ocean-Land-Atmosphere Studies, Calverton, MD
1993-1997	Research Scientist, Center for Ocean-Land-Atmosphere Studies, Calverton, MD
1985-1993	Faculty Research Assistant, COLA, University of Maryland, College Park, MD
1987-1989	Product Developer, VM Systems Group, Arlington, VA
1987	Meteorologist, RDS Inc, Glen Dale, MD
1984-1987	Systems Engineer, MITRE Corp, McLean, VA
1984	Systems Programmer, RMS Technologies, Landover, MD
1983	Engineer, GTE Sprint, San Mateo, CA
1982-1983	Systems Engineer, MITRE Corp, McLean, VA
1979-1982	Scientific Programmer, Sigma Data Corp, Greenbelt, MD

Education:

1978-1979	Graduate studies in Computer Science, Northern Illinois University, Dekalb, IL
1978	B.A. Meteorology, Northern Illinois University, DeKalb, IL

Awards:

American Meteorological Society Special Award *for the development and implemenation of techniques for graphic analysis and visualization of global data sets*. January, 1999.

Computer Skills:

Languages: C, C++, Java, HTML, XML, ALC, FORTRAN, Perl, UNIX Shell, GSL
Operating System Administration: UNIX (and Linux), MS Windows, VMS, MVS, VM

Selected Publications:

Wielgosz, J., B. Doty, J. Gallagher, and D. Holloway, 2001 (accepted for presentation): GrADS and DODS. *Seventeenth International Conference on Interactive Information and Processing Systems* (Albuquerque NM, January 14-19, 2001).

Tsai, P. and B.E. Doty, 1998: A Prototype Java Interface for the Grid Analysis and Display System (GrADS). *Fourteenth International Conference on Interactive Information and Processing Systems* (Pheonix, AZ 11-16 January, 1998).

Dirmeyer, P.A., B.E. Doty and J.L. Kinter III, 1997: Predicting Wintertime Skill from Ensemble Characteristics in the NCEP Medium Range Forecasts over North America. COLA Technical Report #42. 31pp.

Doty, B.E. and J.L. Kinter III, 1995: Geophysical Data Analysis and Visualization using GrADS. Visualization Techniques in Space and Atmospheric Sciences, eds. E.P. Szuszczewicz and J.H. Bredekamp. (NASA, Washington, D.C.), 209-219.

Paolino, D.A., Q. Yang, B. Doty, J. Kinter, J. Shukla, D. Straus, 1995: Results of a Pilot Reanalysis Project at COLA. *Bull. Amer. Meter. Soc*., **76**, 697-710.

Doty, B., and J.L. Kinter III, 1993: The Grid Analysis and Display System (GrADS): a desktop tool for earth science visualization. *American Geophysical Union 1993 Fall Meeting* (San Fransisco, CA, 6-10 December 1993).

Doty, B. and J.L. Kinter III, 1992: The Grid Analysis and Display System (GrADS): A practical tool for earth science visualization. Eigth International Conference on Interactive Information and Processing Systems (Dallas TX, 5-10 January, 1992).

Kenneth E. Mitchell
Curriculum Vita
November 2000

PRESENT POSITION: Senior Scientist, Research Meteorologist
Land Sciences Team Leader
Environmental Modeling Center
National Centers for Environmental Prediction (NCEP)
Phone: 301-763-8000 ext 7225
Email: Kenneth.Mitchell@noaa.gov

EDUCATION:

Degree	Date	Major	Institution
Ph.D.	1979	Meteorology	The Pennsylvania State University
M.S.	1975	Meteorology	The Pennsylvania State University
B.S.	1973	Meteorology	The Pennsylvania State University

PROFESSIONAL EXPERIENCE (some concurrent):

1988-present:	Senior Scientist, land-surface modeling, NCEP/EMC (NOAA/NWS)
1983-1999:	NWP modeling, Reserve Weather Officer, Air Force Weather Agency
1982-1988:	NWP modeling, Atmospheric Physicist, Air Force Geophysics Laboratory
1978-1982:	NWP modeling, Remote Sensing, Air Force Global Weather Central
1979-1981:	Adjunct Professor of Meteorology, Dept of Physics, Creighton University
1973-1978:	Research Assistant, Dept of Meteorology, Pennsylvania State University
1974-1976:	Summer Research Fellow, Visiting Scientist Program, NCAR

HONORS AND AWARDS:
- awarded B.S. as a Highest Distinction Honor Graduate at Penn State
- awarded distinguished UCAR Fellowship while in graduate school at Penn State
- Offutt AFB Junior Officer of the Quarter Award in Fall of 1979
- Scientific Achievement Award in 1984 at Air Force Geophysics Lab (AFGL)
- Air Force Systems Command Certificate of Merit in 1985 at AFGL
- Outstanding Military Airlift Command IMA Reservist of the Year 1988
- Air Force Achievement Medal 1988
- Elected as AMS "Fellow" in October 2000

RECENT PUBLICATIONS:
Chen, F., **K. Mitchell**, J. Schaake, Y. Xue, H. Pan, V. Koren, Q. Duan, M. Ek, and A. Betts,1996: Modeling of land surface evaporation by four schemes and comparison with FIFE observations. *J. Geophys. Res*., **101**, 7251-7268.

Berbery, E., E. Rasmusson, and **K. Mitchell**, 1996: Studies of North American continental-scale hydrology using Eta model forecasts. *J. Geophys. Res*., 101, 7305-7319.

Yarosh, E., C. Ropelewski, and **K. Mitchell**, 1996: Comparison of humidity observations and Eta model analyses and forecasts for water balance studies. *J. Geophys. Res*., 101, 23289-23298.

Basist, A., D. Garrett, R. Ferraro, N. Grody, and **K. Mitchell**, 1996: A comparison between snow cover products derived from visible and microwave satellite observations. *J. Appl. Meteor*., 35, 163-177.

Schaake, J., V. Koren, Q. Duan, **K. Mitchell**, and F. Chen, 1996: Simple water balance model for estimating runoff at different spatial and temporal scales. *J. Geophys. Res*., **101**, 7461-7475.

Sellers, P., B. Meeson, J. Closs, J. Collatz, F. Corprew, D. Dazlich, F. Hall, Y. Kerr, R. Koster, S. Los, **K. Mitchell**, J. McManus, D. Myers, K. Sun, and P. Try, 1996: The ISLSCP Initiative I Global Datasets: Surface boundary conditions and atmospheric forcings for land-atmosphere studies. *Bull. Amer. Meteor*. Soc., **77**, 1987-2005.

Eric F. Wood

Present Address: Department of Civil and Environmental Engineering
Princeton University, Princeton, N.J. 08544
Telephone: (609) 258-4675; FAX: (609) 258-2799
E-Mail: efwood@princeton.edu

Degrees:
1970 - B.A.Sc. (honours) Civil Engineering, Univ. of British Columbia, Vancouver, Canada
1972 - S.M., Civil Engineering, MIT, Cambridge, Massachusetts
1973 - C.E., Civil Engineering, MIT, Cambridge, Massachusetts
1974 - Sc.D., Civil Engineering, MIT, Cambridge, Massachusetts

Areas of Interest: Hydroclimatology with emphasis on land atmospheric interactions, remote sensing of terrestrial hydrologic systems, hydrologic impacts from climate change.

Current Rank:
Professor, Department of Civil and Environmental Engineering, Princeton University.
Faculty member: Program in Environmental Engineering and Water Resources; Atmospheric and Oceanic Science Program; the Princeton Environmental Institute

Administrative Positions (held at Princeton University):
July 1994 - June 1997: Director of Graduate Studies, Department of Civil Engineering and Operations Research,
July 1986 - June 1987**:** Acting Chairman, Department of Civil Engineering and Operations Research
July 1980 - June 1994: Director, Water Resources Program, Princeton University

Current Professional Activities (selected):
NAS/NAE, Water Science and Technology Board
Board on Atmospheric Sciences and Climate
Committee on Hydrological Sciences
Climate Research Committee
World Climate Research Program, Global Energy and Water Experiment (GEWEX), Coupled Model Research Panel
American Geophysical Union, Union Fellows Committee, Remote Sensing Committee
NASA, Earth Observing System (EOS), Member EOS Science Executive Committee
American Meteorological Society, Member, AMS Council, Hydrology Committee

Awards and Honors:
1977 Robert E. Horton Award (presented by the American Geophysical Union)
1980 Rheinstein Award, Princeton University
1993 Fellow, American Geophysical Union
1997 Fellow, American Meteorological Society
2001 Robert E. Horton Lecturer, American Meteorological Society

Selected Journal and Book Publications: (from a total exceeding 125):
Land Surface - Atmosphere Interactions for Climate Modeling, Kluwer Acad. Pub., Dordrecht, The Netherlands, 1991.
Scale Effects in Hydrology, V.J. Gupta, I. Rodriguez-Iturbe and E.F. Wood (ed.), Reidel, Dordrecht, 245 p., 1986.
Dubayah, Ralph O., Eric F. Wood, Edwin T. Engman, Kevin P. Czajkowski, Mark Zion and Joshua Rhoads (2000) “Remote Sensing in Hydrological Modeling”, Chapter 5 in Remote Sensing in Hydrology and Water Management, G. Schutze and E. Engman (Eds.), Springer, Berlin, pp 85-102.
Pauwels, V.R.N., and E.F. Wood, (1999) A soil-vegetation-atmosphere transfer scheme for the modeling of water and energy balance processes in high latitudes. 2. Application and validation, *Journal of Geophysical Research*, 104(D22) 27823-27840.
Liang, X., E.F. Wood, and D.P. Lettenmaier, “Modeling ground heat flux in land surface parameterization schemes”, *Journal of Geophysical Research*, 104(D8); 9581-9600, 1999.
Wood, Eric F. 1999. "The role of lateral flow: over- or underrated?" Chp. 10 in Eds. J. D. Tenhunen and P. Kabat *Integrating hydrology, ecosystem dynamics, and biogeochemistry in complex landscapes*, JohnWiley & Sons, Chichester, pp. 197-216.

A. SCOTT DENNING

Education:

B.A., Geological Sciences, 1984. University of Maine, Orono, Maine. Highest Honors.

M.S., Atmospheric Science, 1993. Colorado State University, Ft. Collins, Colo.

Ph.D. Atmospheric Science, 1994. Colorado State University, Ft. Collins, Colo.

Experience:

1998– : *Assistant Professor*, Department of Atmospheric Science, Colorado State University Atmosphere-biosphere interactions. Global biogeochemical cycles. Land-surface climate..

1996–98 : *Assistant Professor*, Donald Bren School of Environmental Science and Management, University of California, Santa Barbara.

1994–96: *Postdoctoral Research Associate*, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523. David A. Randall, supervisor. (NASA supported).

Selected Publications:

Denning, A. S., I. Y. Fung, and D. A. Randall, 1995: Latitudinal gradient of atmospheric CO_2 due to seasonal exchange with land biota. *Nature*, **376**, 240-243.

Randall, D. R., P. J. Sellers, J. A. Berry, D. A. Dazlich, C. Zhang, J. G. Collatz, A. S. Denning, S. O. Los, C. B. Field, I. Fung, C. O. Justice, and C. J. Tucker, 1996: A revised land-surface parameterization (SiB2) for GCMs. Part 3: The greening of the Colorado State University General Circulation Model. *Journal of Climate*, **9**, 738-763.

Denning, A. S., J. G. Collatz, C. Zhang, D. A. Randall, J. A. Berry, P. J. Sellers, G. D. Colello, and D. A. Dazlich, 1996. Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part 1: Surface carbon fluxes. *Tellus*, **48B**, 521-542.

Denning, A. S., D. A. Randall, G. J. Collatz, and P. J. Sellers, 1996. Simulations of terrestrial carbon metabolism and atmospheric CO_2 in a general circulation model. Part 2: Spatial and temporal variations of atmospheric CO_2. *Tellus*, **48B**, 543-567.

Zhang, C., D. A. Dazlich, D. A. Randall, P. J. Sellers, and A. S. Denning, 1996: Calculations of the global land surface energy, water, and CO_2 fluxes with an off-line version of SiB2. *Journal of Geophysical Research*, **101**, 19061-19075.

Sellers, P. J., R. E. Dickinson, D. A. Randall, A. K. Betts, F. G. Hall, J. A. Berry, C. J. Collatz, A. S. Denning, H. A. Mooney, C. A. Nobre, and N. Sato, 1997. Modeling the exchanges of energy, water, and carbon between the continents and the atmosphere. *Science*, **275**, 502-509.

Ciais, P., A. S. Denning, P. P. Tans, J. A. Berry, D. A. Randall, G. J. Collatz, P. J. Sellers, J. W. C. White, M. Trolier, H. J. Meijer, R. J. Francey, P. Monfray, and M. Heimann, 1997: A three-dimensional synthesis study of $\delta^{18}O$ in atmospheric CO_2. Part 1: Surface fluxes. *Journal of Geophysical Research*, **102**, 5857-5872.

Pielke, R. A., R. Avissar, M. Raupach, H. Dolman, X. Zeng, and S. Denning, 1998. Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. *Global Change Biology*, **4**, 101-115.

Denning, A. S., M. Holzer, K. R. Gurney, M. Heimann, R. M. Law, P. J. Rayner, I. Y. Fung, S.-M. Fan, S. Taguchi, P. Friedlingstein, Y. Balkanski, J. Taylor, M. Maiss, and I. Levin, 1999. Three-dimensional transport and concentration of SF_6: A model intercomparison study (TransCom 2). *Tellus*, **51B**, 266-297.

Denning, A. S., T. Takahashi and P. Friedlingstein, 1999. Can a strong atmospheric CO_2 rectifier effect be reconciled with a "reasonable" carbon budget? *Tellus*, **51B**, 249-253.

Land Information System

Submitted to CAN-00-OES-01: Grand Challenge Applications in the Earth, Space, Life, and Microgravity Sciences

P. R. Houser[1], C. Peters-Lidard[1], P. Dirmeyer[2], B. Doty[2], K. Mitchell[3], E. Wood[4], S. Denning[5]

[1]*NASA's Goddard Space Flight Center(GSFC), Greenbelt, MD 20771*

[2]*Center for Ocean-Land-Atmosphere Studies(COLA), Calverton, MD 20705*

[3]*National Centers for Environmental Prediction (NCEP), Camp Springs, MD 20746*

[4]*Princeton University, Department of Civil and Environmental Engineering, Princeton, NJ 08544*

[5]*Colorado State University (CSU), Department of Atmospheric Science; Fort Collins, CO 80523*

5. Milestones, Schedule, and Costs

Milestone	Expected Completion Date
5.1 Required Investigator Milestones	
A) Software engineering plan completed	*Jun 2002*
Deliver software engineering plan, including software development plan, configuration management plan and quality assurance plan. Appoint Review Board consisting of at least one NASA representative.	
E) Global LDAS Code baseline completed	*Jul. 2002*
Baseline NOAH and CLM codes within the Global LDAS at 1/4 degree resolution on ESS Testbed for near-term retrospective period. Initial version of documented source code made publicly available via the Web. Deliver initial versions of requirements document and software design documents via the Web.	
B) FY02 Annual Report delivered to ESS via Web	*Aug. 2002*
H) Design policy for interoperability and community delivery agreed on.	*Feb. 2003*
Define and deliver documents defining interoperability and community requirements. Updated requirements document and design documents delivered via Web. Initial version of test plan delivered via Web. All documents submitted to Review Board.	
F) First code improvement completed	*Mar. 2003*

Improve NOAH and CLM codes within the Global LDAS to operate at a 5 km horizontal spatial resolution with a throughput of approximately 1 ms per grid cell per day of execution on ESS Testbed for near-term retrospective period. Provide code scaling curves via the Web. Documented source code made publicly available via the Web.

I) Interoperability prototype from milestone "H" tested with improved codes *Jul. 2003*

Demonstrate improved NOAH and CLM codes on the LIS Cluster installed in f). Demonstrate VIC code on ESS Testbed and LIS cluster implemented according to H). Update Requirements, Design, and Test documents and deliver via Web. Submit initial Test Report for interoperability test. Submit initial User's Guide. All documents submitted to Review Board.

C) FY03 Annual Report delivered to ESS via Web *Aug. 2003*

G) Second code improvement completed *Feb. 2004*

Implement the Land Information System (LIS) to integrate database and visualization functions with Global LDAS. Improve NOAH, VIC and CLM codes within the Global LIS to operate at a 1 km horizontal spatial resolution with a throughput of approximately 0.4 ms per grid cell per day of execution (approximately a factor of 2.5 speedup) LIS cluster for near-term retrospective period. Provide code scaling curves via the Web. Documented source code made publicly available via the Web.

J) Full interoperability demonstrated using improved codes *Jul. 2004*

Given that a prototype ESMF-compliant version of CLM is received by June 2003, implement the prototype ESMF-compliant version of CLM in the Global LIS and evaluate performance relative to milestones E), F) and G). Deliver documented source code via the Web, and submit updated documents to Review Board.

K) Customer delivery accomplished *Aug. 2004*

Demonstrate LIS/ESMF functionality using ESMF-compliant version of CLM from milestone J) as well as existing versions of CLM, NOAH and VIC. Analyze predictive capability of the LIS using GrADS/DODS and web interfaces, with users at NCEP, COLA and Universities. Submit updated Test Plans reflecting portability test, updated User's Guide, Maintenance Manual, and Requirements and Design documents. Present results to Review Board. Documented source code made publicly available via the Web.

D) Final Report delivered to ESS via Web *Feb. 2005*

TOTAL Required Milestones

5.2 Optional Investigator Milestones

f) Installation of a PC cluster at an Investigator's home site *Aug. 2002*

Install a Linux cluster at NASA/GSFC, consisting of two "queen" nodes and at least 192 "compute" nodes connected by at least fast ethernet. The queen nodes will support control and I/O functions and consist of dual 1.5 GHz processors, 4 GB RAM, and 2 TB storage or better. The compute nodes will support computations and consist of single 1.2 GHz processors, 512 MB RAM, and 80 GB storage or better. We anticipate gigabit connections between the compute node switches and the queen nodes as well as between the queen nodes and the GSFC network.

TOTAL Optional Milestones

GRAND TOTAL

Certification Regarding Lobbying
for Contracts, Grants, Loans, and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No Federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any Federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form - LLL, "Disclosure Form to Report Lobbying," in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers (including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements) and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, title 31, U.S. Code. Any person who fails to file the required certificate shall be subject to a civil penalty of not less than $10,000, and not more than $100,000 for each such failure.

____________________________________ ________________________

Signature Date

Dr. Franco Einaudi, Director of Earth Sciences

Name and Title of Authorized Representative

NASA Goddard Space Flight Center

Organization Name

Certification Regarding
Debarment, Suspension, and Other Responsibility Matters
Primary Covered Transactions

This certification is required by the regulations implementing Executive Order 12549, Debarment and Suspension, 34 CFR Part 85, Section 85.510, Participant's responsibilities. The regulations were published as Part VII of the May 26, 1988 Federal Register (pages 19160 - 19211). Copies of the regulation may be obtained by contacting the U.S. Department of Education, Grants and Contracts Service, 400 Maryland Avenue, S.W. (Room 3633 GSA Regional Office Building No. 3), Washington, DC. 20202-4725, telephone (202) 732-2505.

(1) The prospective primary participant certifies to the best of its knowledge and belief, that it and its principals:

(a) Are not presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency;

(b) Have not within a three-year period preceding this proposal been convicted of or had a civil judgment rendered against them for commission of fraud or a criminal offense in connection with obtaining, attempting to obtain, or performing a public (Federal, State, or Local) transaction or contract under a public transaction; violation of Federal or State antitrust statutes or commission of embezzlement, theft, forgery, bribery, falsification or destruction of records, making false statements, or receiving stolen property;

(c) Are not presently indicted for or otherwise criminally or civilly charged by a governmental entity (Federal, State, or Local) with commission of any of the offenses enumerated in paragraph (1)(b) of this certification; and

(d) Have not within a three-year period preceding this application/proposal had one or more public transactions (Federal, State, or Local) terminated for cause or default.

(2) Where the prospective primary participant is unable to certify to any of the statements in this certification, such prospective participant shall attach an explanation to this proposal.

NASA Goddard Space Flight Center	**Land Information System**
Organization Name	PR/Award Number or Project Name

Dr. Franco Einaudi, Director of Earth Sciences

Name and Title of Authorized Representative

Signature	Date

ED Form GCS-008 (REV.12/88)

Assurance of Compliance with the National Aeronautics
and Space Administration Regulations Pursuant to
Nondiscrimination in Federally Assisted Programs

The NASA Goddard Space Flight Center,
(*Institution, corporation, firm, or other organization on whose behalf this assurance is signed, hereinafter called "Applicant")*

HEREBY AGREES THAT it will comply with Title VI of the Civil Rights Act of 1964 (P.L. 88-352), Title IX of the Education Amendments of 1962 (20 U.S.C. 1680 et seq.), Section 504 of the Rehabilitation Act of 1973, as amended (29 U.S.C. 794), and the Age Discrimination Act of 1975 (42 U.S.C. 16101 et seq), and all requirements imposed by or pursuant to the Regulation of the National Aeronautics and Space Administration (14 CFR Part 1250) (hereinafter call "NASA") issued pursuant to these laws, to the end that in accordance with these laws and regulations, no person in the United States shall, on the basis of race, color, national origin, sex, handicapped condition, or age be excluded from participation in, be denied the benefits of, or be otherwise subjected to discrimination under any program or activity for which the Applicant receives federal financial assistance from NASA; and HEREBY GIVE ASSURANCE THAT it will immediately take any measure necessary to effectuate this agreement.

If any real property or structure thereon is provided or improved with the aid of federal financial assistance extended to the Applicant by NASA, this assurance shall obligate the Applicant, or in the case of any transfer of such property, any transferee, for the period during which the real property or structure is used for a purpose for which the federal financial assistance is extended or for another purpose involving the provision of similar services or benefits. If any personal property is so provided, this assurance shall obligate the Applicant for the period during which it retains ownership or possession of the property. In all other cases, this assurance shall obligate the Applicant for the period during which the federal financial assistance is extended to it by NASA.

THIS ASSURANCE is given in consideration of and for the purpose of obtaining any and all federal grants, loans, contracts, property, discounts, or other federal financial assistance extended after the date hereof to the Applicant by NASA, including installment payments after such date on account of applications for federal financial assistance which were approved before such date. The Applicant recognized and agrees that such federal financial assistance will be extended in reliance on the representations and agreements made in this assurance, and that the United States shall have the right to seek judicial enforcement of this assurance. This assurance is binding on the Applicant, its successors, transferees, and assignees, and the person or persons whose signatures appear below are authorized to sign on behalf of the Applicant.

Dated: ____ Applicant: ____

By: **Dr. Franco Einaudi, Director of Earth Sciences**
(*President, Chairman of Board, or Comparable Authorized Person)*

Earth Sciences Directorate, Code 900
NASA Goddard Space Flight Center
Greenbelt, MD 20771
(Applicant's mailing address)

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